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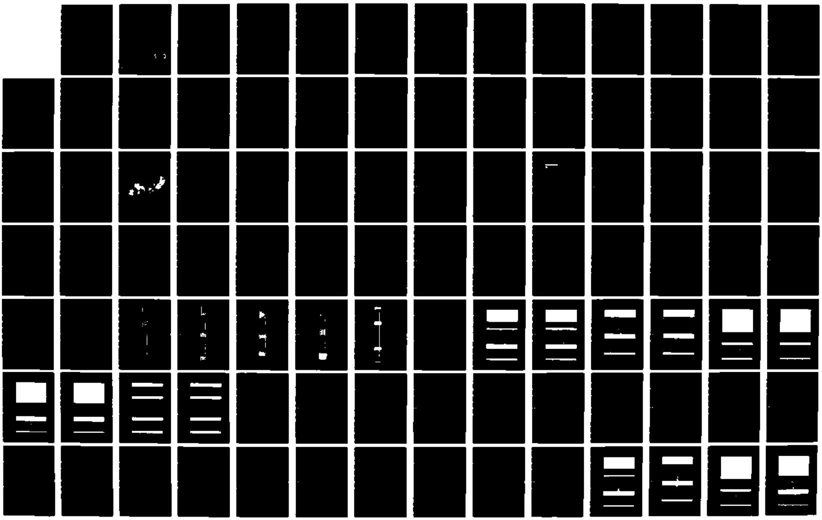

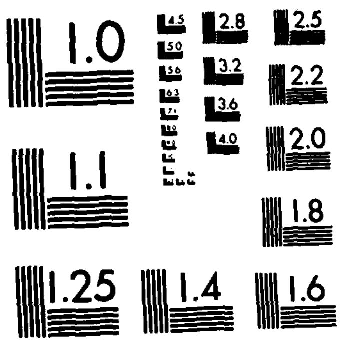

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Washington, D.C. 20591

Alaska Loran-C Flight Test Evaluation

Larry D. King
Edwin D. McConkey

March 1983

Final Report

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16. Abstract

This report contains the description and results of a Loran-C flight test program conducted in the State of Alaska. The testing period was from August 1982 to September 1982. The purpose of the flight test was to identify applicable Loran-C accuracy data for the Alaskan air taxi and light aircraft operators so that a Supplemental Type Certificate (STC) can be issued in the Alaska Region for the Loran-C system tested (Teledyne TDL-711).

Navigation system errors were quantified for the Loran-C unit tested. The errors were computed from knowledge of position calculated from ground truth data and the indicated position of the navigator. Signal coverage, bias and flight technical error data were also obtained. Multilateration ground truth, photographic ground truth, and data acquisition systems were carried aboard the test aircraft.

The tests were concentrated in the southwest part of the Alaskan mainland. An interconnecting network of routes west of Anchorage and south of a line from Fairbanks to Kotzebue were flown for data collection. Of particular interest was the area around, and to the west of, Bethel where there are currently very few aids to air navigation.

The North Pacific Loran-C chain with stations at St. Paul Island (Master), Port Clarence (Yankee) and Narrow Cape (Zulu) was used in this area. Test results indicate that Loran-C has sufficient signal coverage and accuracy to support aircraft enroute navigation in much of the test area. In the area around Anchorage the test unit failed to consistently acquire and track the signal, however. Further analysis of the data and testing are required in the Anchorage area.

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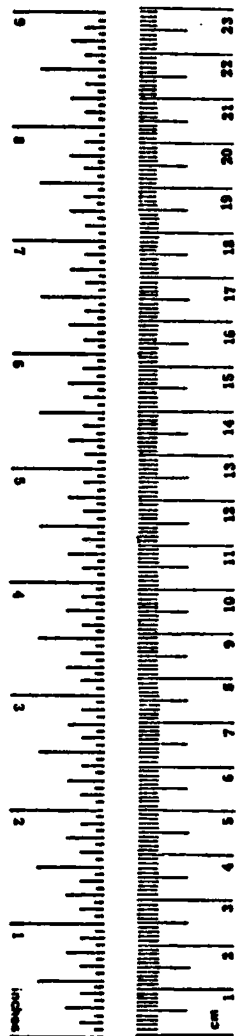
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

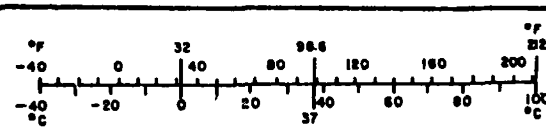
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 EXECUTIVE SUMMARY

This report describes the results of a program for the collection of flight test data in Alaska using Loran-C (a wide area coverage navigation system). The purpose of the flight test was to evaluate a Loran-C receiver as an enroute navigation aid in Alaska and to collect data that can be submitted to the FAA in support of an application for a Supplemental Type Certificate (STC). Ultimately the Loran-C performance data collected will be utilized in the consideration of Loran-C by the Alaskan Region as an enroute navigation aid for the Alaska air taxi operators and light aircraft operators.

Navigation system errors in alongtrack and crosstrack coordinates were quantified for the Loran-C unit tested (Teledyne TDL-711). Total system crosstrack error and alongtrack error were also quantified in this report. Signal coverage, bias and flight technical error data, collected for detailed analysis, were obtained from DME multilateration ground truth, photographic ground truth and data acquisition systems carried aboard the test aircraft. Included in the test were equipment shakedown flights for the data acquisition system, transition data collection flights and Alaska data collection flights.

1.1 OBJECTIVES

The objective of this project was to collect Loran-C performance data in Alaska that would be applicable in the consideration of Loran-C by the FAA as an enroute navigation aid. The specific objectives of this flight test were defined as follows:

- Collect Loran-C data relating to signal coverage and navigation system accuracy in the Alaska enroute structure.
- Collect and analyze Loran-C data while enroute to Alaska.
- Collect and analyze signal information such as propagation errors, signal to noise ratios, etc.
- Collect and analyze fixed site Loran-C data so that the effects of signal anomalies can be identified in the flight data.
- Qualitatively evaluate the potential for, and the effects of, operator errors using the Loran-C airborne system selected.
- Collect and analyze system error data associated with the airborne Loran-C system selected.
- Provide the necessary installation and accuracy data so that a Supplemental Type Certificate (STC) can be issued by the FAA for the Loran-C system tested.

1.2 FLIGHT TEST ROUTES AND PROCEDURES

A total of 6,300 data miles were flown in the State of Alaska during a period from September 1, 1982 to September 10, 1982. Test locations were chosen to include as many geographically diverse situations as possible within the constraints of the test program.

In order to meet the primary objective of obtaining a STC for the TDL-711 Loran-C receiver, the major factors in designing the test routes were defined as follows: (1) determine the area of usable, accurate signal coverage, and (2) determine avionics accuracy within that coverage. The test routes shown in Figure 1.1 were located in the southwest part of the state where there is coverage from the North Pacific Loran-C chain. Single triad coverage was available from the Master Station at St. Paul Island and the secondary stations at Port Clarence and Narrow Cape. The other secondary station in the chain at Attu Island was utilized only as a backup station.

Accuracy data were collected whenever the DME ground truth system was operational. A minimum of two received DME stations and satisfactory station geometry was required of the DME system. In order to be considered as having satisfactory station geometry, the expected accuracy of the DME system had to exceed 0.15 nm (1σ). In those cases were DME coverage was poor (west of Bethel) the photographic ground truth system was utilized.

To demonstrate compatibility with the existing VOR/DME system and air taxi operator routes, all of the flight test routes were along published, low altitude airways. An additional flight was flown west of Bethel to the following locations; KIPNUK, MEKORYUK, NIGHTMUTE, CAPE ROMANZOF and RUSSIAN MISSION. The purpose of this segment was to explore overall signal accuracy and coverage and to demonstrate operations similiar to those normally made by local air taxi operators. Photographic data were collected to verify the accuracy of the Loran-C navigator in this area.

1.3 FLIGHT CREW

Three subject pilots were utilized for this test effort. All of the pilots were commercial and instrument rated, and all had previous experience flying long range navigation equipment. Table 1.1 presents a breakdown of the flight hours and qualifications for each pilot.

Table 1.1 Project Pilot Experience

PILOT	TOTAL TIME	COMM.	INST.	ATR	PREVIOUS LONG RANGE NAV. EXP.
A	35,000 hrs	✓	✓	✓	Omega
B	35,000 hrs	✓	✓	✓	Omega
C	2,000 hrs	✓	✓		Loran-C

All test routes were flown by the primary subject pilot. The copilot acted as safety observer and was also responsible for ATC communications and data entry into the TDL-711 Loran-C system. The flight test observer was tasked with operation of the data acquisition

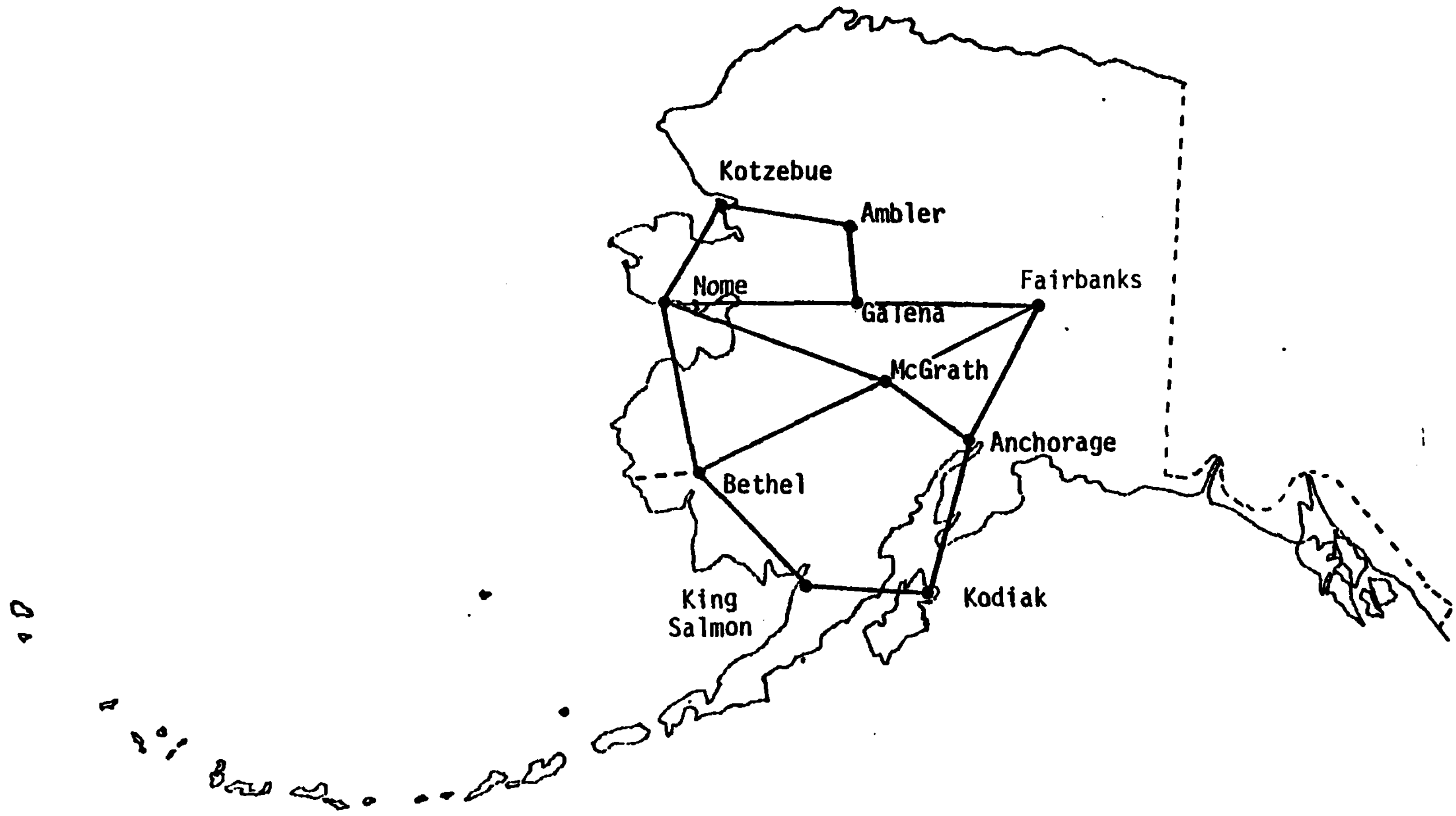

Figure 1.1 Alaska Loran-C Flight Test Routes

system and the manual logging of unusual flight situations, such as, deviations due to weather or ATC requests.

1.4 TEST VEHICLE AND EQUIPMENT

The aircraft used in the test was a twin engine Beechcraft Queen Air Model 65. This vehicle was chosen for its economy, large cabin space and gross weight payload capability. Data acquisition equipment was well within maximum gross weight limits with a full load of fuel, full crew and required test support personnel.

During the data collection activity, a dedicated course deviation indicator (CDI) display was utilized to display Loran-C steering commands at all times. The safety observer monitored aircraft position by standard VOR navigation using a standard CDI display on the right side of the front instrument panel. The Loran-C airborne system used for the flight test program was a Teledyne TDL-711 Micro-Navigator system consisting of an E-field vertical antenna; a receiver/computer unit mounted on the data acquisition rack; a control display unit (CDU) mounted on the aircraft's center console; and a CDI in the center of the pilot's instrument panel to display Loran-C course deviation.

The output of the Loran-C navigator drives a deviation indicator (CDI), giving linear deviation from the selected "TO" waypoint course. Full scale deflection left or right of center is 1.28 nautical miles. The "TO" flag indicates that the aircraft is located short of the "TO" waypoint. The "FROM" flag indicates a position beyond the "TO" waypoint. The red "NAV" flag indicates that steering commands are invalid.

The Loran-C receiver is designed to run a remote display unit (RDU), and the information it provides to that remote display can be externally programmed. These data were received by the data acquisition system.

1.5 REFERENCE SYSTEMS

A multiple DME positioning system and a photographic positioning system were used to fix the aircraft's actual position. The multiple DME positioning system was a Rockwell-Collins DME-700. The DME-700 transmits pulsed signals to a ground station and receives responses from the station. Slant range is determined by measuring the transmit time from the aircraft to the station and back to the aircraft. The DME-700 was operated in scan mode for this test. Scan mode provides a capability to service up to five stations at a high pulse rate, and can scan the other 274 channels for valid replies at a lesser rate.

Loran-C data from the TDL-711, DME data from the DME-700, and aircraft systems data were recorded on a microprocessor controlled data collection system. Data were recorded at a 1 Hz rate on tape cassettes.

The photographic positioning system used was Minolta X-700 camera system. The Minolta X-700 is a 35 mm Single Lens Reflex (SLR) camera system. Options available for the X-700 system that were utilized for this flight test program are as follows:

- Multifunction back
- MD-1 Motor Drive
- Remote Control

The multifunction back allows the user to imprint on each negative one of several items: time (hours, minutes and seconds), calendar date (month, day and year) or it can be programmed to number each negative in sequence from 1 to 999,999. For this flight test application the time option was utilized. This allowed the data to be time correlated with the airborne system data collector. The motor drive and remote control options allowed the flight test engineer to operate the camera while observing other necessary data collection parameters.

The camera was mounted inside the aircraft pointing through the bottom of the fuselage. Two lenses were used (35 mm and 70 mm), depending on the altitude above the ground, to yield a reasonable field of view. Photographs were taken of airport runways and VOR stations so that an accurate indication of actual aircraft position could be determined. Photographs were developed on site to insure the validity and quality of the data.

Through the use of the aircraft's true position, and the navigation and Loran-C data recorded from the Loran-C navigator, many accuracy parameters could be determined. These include:

- easting and northing position errors
- Loran-C time difference errors
- total system alongtrack and crosstrack errors
- navigation sensor alongtrack and crosstrack errors
- navigation computer alongtrack and crosstrack errors
- flight technical error

The error components were evaluated statistically by computing their mean values and standard deviations according to standard formulas.

Time difference errors were computed at each point where valid Loran-C and DME position data was available. The procedure involves reversing the coordinate conversion process performed by the TDL-711 navigator. Using the true aircraft position from the DME system, distance to Loran-C station values are computed for a spheroidal earth model.

1.6 DATA PROCESSING

The data obtained during the flight test consisted of digital data recordings on magnetic tape, photographic data at select sites and observations of the pilots and flight test observer. The digital data recording system, used in the test, recorded three generic types of navigation and aircraft system data. These types were:

- analog voltage or phase angle data
- DME digital data
- TDL-711 Loran-C digital data

All data were time tagged by the data collector clock to the nearest .01 second. Data were recorded at a 1Hz rate on magnetic tape cassettes. On the transition flight from West Palm Beach to Anchorage, data were recorded at periodic intervals of approximately five minutes on line and five minutes off line. During the Alaskan flight testing and the return flight to West Palm Beach data were recorded continuously. In all, 120 cassettes of test data were obtained. Due to the large amount of data, processing was performed at a 0.1 Hz rate thereby providing data at ten second intervals.

The following analog data were recorded during the test and utilized in the data reduction procedure:

- dynamic pressure (indicated airspeed)
- altitude reference } potentiometer voltages
- altitude wiper }
- aircraft heading synchro
- CDI indicator voltage
- CDI flag voltage

Seven DME data channels from the Rockwell-Collins DME-700 were obtained each second. Each channel contained a time tag, co-channel VOR frequency and DME distance. In areas where there were five or more DME stations available, the DME-700 provided DME measurements from five separate stations. The additional two channels contained data from two of the five channels taken about a half second later. When fewer than five stations were available, the DME-700 provided repeated measurements from the available stations to complete the seven channels of data.

The DME data were utilized to compute true aircraft position. The procedure required the use of a data base containing the latitude/longitude coordinates of the VORTAC/DME stations, station elevation and station frequency. A least squares error minimization procedure was developed and used to compute aircraft position. The control loop parameters on the position computation procedure were set to values which would provide position accuracy to 0.15 nm (1σ).

The TDL-711 Loran-C navigator was equipped with a specialized programmable read-only memory (PROM) for providing a large amount of Loran-C receiver information through the remote display unit (RDU) data line. The Loran-C information is divided into three general categories, display replica data, Loran-C signal processing data and Loran-C navigation data.

1.7 RESULTS

The following results of the Alaska flight tests are derived from operational observations of the flight crew, detailed analysis of the recorded and processed test data, the photopraphic data and data provided by the Coast Guard monitor station near Kodiak, Alaska.

1.7.1 Chain Performance

During the Alaska flights the North Pacific chain was utilized almost exclusively. On a few occasions in the Anchorage area when the receiver would not acquire the North Pacific chain, attempts were made to acquire the Gulf of Alaska chain. These attempts were equally unsuccessful and so the only useful navigation data were obtained with the North Pacific chain. The triad used for navigation was:

time difference A - Port Clarence/St. Paul Island
time difference B - Narrow Cape/St. Paul Island

As determined from Coast Guard monitor data, the North Pacific chain was operating within the normal time difference accuracy and system availability ranges during the performance of the flight tests. Since the date of the test, the Coast Guard has modified the control ECD on the master station. The Coast Guard believes that this change will likely improve ECD values in the flight test area.

1.7.2 DME System Performance

By far the greatest single problem in using the DME positioning system in Alaska is the paucity of DME stations in the test area. DME coverage was quite good in the Anchorage, Fairbanks and Nome areas where four to five stations were usually received. DME coverage was satisfactory in the King Salmon and Bethel areas where two to three stations were received. Coverage was unsatisfactory in the areas around McGrath, Ambler and Kotzebue where zero to two stations were received. Often, when two stations were received, they were both near the same airport, one being an enroute VORTAC, the other being an ILS DME facility. In these instances no valid DME positioning was possible due to the poor system geometry.

1.7.3 Receiver Performance

In the Anchorage and Fairbanks areas, the availability of Loran-C guidance from the TDL-711 was very poor. This was consistenly true on each day that the unit was flown in these areas. Approximately fifty to sixty miles west of a line between Anchorage and Fairbanks, the receiver consistently acquired the test triad and the receiver availability was very good throughout this part of the test area.

Time difference errors were evaluated by computing time difference values which would produce zero position error and subtracting the time difference value recorded during the test. Evaluation of the time difference error in this manner provided information on the receiver's ability to process the Loran-C signal and identify the proper cycle crossing and evaluate the propagation model used by the navigator for position determination.

Numerous instances of cycle selection difficulties were observed in the eastern part of the test area. This was particularly true in the flights in the Anchorage and Fairbanks areas when the receiver had

acquired the signal. Possible cycle selection problems producing time difference errors of ±10 microseconds were observed at Nome and Bethel on one occasion.

Propagation model errors, where they would be separated from cycle selection errors, were quite consistent with expected performance. The TDL-711 propagation model uses a faster propagation velocity than that predicated by theoretical means[4]. It is especially true in the case of signals which propagate over mountainous terrain of poor conductivity, such as the areas west of Fairbanks, Anchorage and Kodiak. These mountains, some of which are the most rugged in North America, appear to have a significant slowing effect on the propagation velocity of the 100 KHz Loran-C signal. This slowing effect coupled with the fast propagation velocity produced apparent propagation model errors with magnitudes of five to six microseconds near Nome and Kodiak. Smaller errors were observed in the center of the test triad coverage area.

Of major concern are the large number of cycle tracking problems observed in these tests. These errors produce large position errors ranging up to 20 nm in the Anchorage area. The TDL-711 system is incapable of detecting these cycle tracking problems at the present time and therefore provides no warning to the pilot.

Of lesser concern for enroute IFR certification are the propagation modeling errors. These errors are generally quite repeatable and capable of being reduced by improved modeling or the use of published corrections. These errors will be of concern if IFR approach certification criteria are to be met in the future.

1.7.4 Coordinate Conversion and Guidance Computation Performance

The procedure for converting time difference measurements to latitude and longitude values was checked at several points in the test area. In all instances the procedure introduced less than .02 nm error. Therefore, the coordinate conversion procedure introduces negligible error into the system performance.

The computation of distance to waypoint and crosstrack deviation was checked throughout the test area. The crosstrack error differed by less than .03 nm and the distance to waypoint differed by less than 0.1 nm, which was the resolution of the recorded data. Therefore, the guidance computation procedure introduces negligible error into the system performance.

1.7.5 Pilot Performance

The flights often encountered high winds and moderate turbulence. In spite of these conditions, the data shows that flight technical error is considerably smaller than the 2.0 nm value contained in Advisory Circular 90-45A for enroute performance. The 95% level (2σ) for flight technical error as determined by the test data was 0.35 n. This is approximately one-sixth of the value used in the advisory circular.

1.7.6 Operational Performance

As found in this test and previous Loran-C tests with the TDL-711, the system has been designed reasonably well from the pilot's point of view. Most of the modes were, at one time or another, used by each of the subject pilots. Each mode of operation was considered logical and was understood by the pilots once the initial familiarization with the system was completed.

Of the greatest concern to the pilots was the unexpected and unannunciated degradation of accuracy in the Anchorage and Fairbanks areas. In some cases the Loran-C accuracy diverged from a value of approximately 1 nm to value approaching 20 nm. From the pilot's point of view the system is performing perfectly (i.e., the system is functioning with an adequate set of signal strengths, the CDI flag is pulled out of view, and CDI steering signals are available). However, without some supplemental position fixing aid such as VOR and DME, or visual fixes, the pilot is not aware that his guidance could be in error by 20 nm.

The TDL-711 system offers a diagnostic mode which can be utilized to display certain internal navigator data such as signal to noise ratios (SNR's) and other important signal data. This mode is entered by moving the selector to the LEG CHG position followed by a series of keystrokes initiated by the pilot. On several occasions when the pilot tried to exit the diagnostic mode, the system displays would become frozen. To resume normal navigation the system had to be reinitialized in flight. This situation is probably of minimal importance unless the pilot is acquainted with, and trained to use, the diagnostic mode.

A similar type of problem occurred on two occasions. For reasons unknown, when a leg change (LEG CHG) was initiated, the CDI needle moved full left then right repeatedly. Again the displays were frozen and the system required reinitialization before navigation could be resumed. Both problems are likely related to software in the navigator.

The last problem is of minimal importance in most instances. When initiating a leg change, a period of several seconds is required, during which time the CDI needle is centered and the flag is in view. In an enroute environment, where course changes between legs are usually moderate, this denial of steering information is not critical. However, if this situation occurred in a terminal area situation where course changes of up to 90° can be expected, this system characteristic could possibly result in undesirable airspace utilization under conditions where airspace is at a premium.

Finally, no noticeable problems were experienced due to precipitation static. Several of the flights were flown in rain, ice and snow for extended periods of time and not once was there experienced a system problem that could be related to precipitation static. Even at times when the rainfall rates were heavy, no noticeable problems were experienced due to precipitation. The extent to which this performance is due to the static wicks installed upon the aircraft is unknown as the aircraft was not instrumented to measure discharge currents.

1.7.7 Photographic Data

Table 1.2 summarizes the results of Alaska Loran-C data collected with the photographic data collection system on the Bethel Spur Route. The data is shown for six selected locations in the area west and north of Bethel. The summary of the error quantities in the table presents the error values for four specific parameters: Northing error (N-error), Easting error (E-error), crosstrack error (XTK-error) and alongtrack error (ATK-error).

Table 1.2 Bethel Spur Route Error Quantities

LOCATION	COURSE	N-ERROR	E-ERROR	XTK-ERROR	ATK-ERROR
KIPNUK	347°	-.375	.438	.339	-.466
	167°	-.316	.417	-.333	.404
MEKORYUK	67°	-.092	.434	.257	.362
	247°	-.087	.482	-.271	-.408
NIGHTMUTE	219°	-.045	.415	-.350	-.228
	39°	-.036	.425	.352	.241
CAPE ROMANZOF	37°	-.131	.367	.371	.116
	37°	-.126	.361	.364	.117
RUSSIAN MISSION	11°	-.277	.532	.575	-.174
	191°	-.207	.552	-.581	.101
BETHEL	24°	-.352	.485	.587	-.124
	24°	-.325	.329	.432	-.163

The values indicated in Table 1.2 support the fact that the TDL-711 system performs very accurately in the Bethel area. As shown in the table, each location was flown twice, therefore demonstrating the repeatable accuracy of the system in good coverage areas.

Comparison of the photo data with the DME positioning data for Bethel on the same day shows excellent agreement. The DME system produced northing and easting errors of -.369 and +.427 nm, respectively. These values agree very well with the northing errors of -.352 nm, and fall in between the easting errors of .485 and .329 nm.

1.7.8 Overall System Performance

Overall the performance of the navigator during the Alaska flights was quite variable. The performance in the Anchorage and Fairbanks areas, at the present time, is not acceptable for IFR navigation. Performance in areas west of the mountainous portions of the test area around King Salmon, Bethel, Aniak and Nome was sufficient to meet Advisory Circular 90-45A standards for RNAV enroute accuracy.

Statistical processing of the data was performed to produce total system alongtrack (TSAT) errors and total system crosstrack (TSCT) errors. These data are shown in Table 1.3.

Table 1.3 Total System Errors

FLIGHT DATE	ERROR TYPE	# PTS	MEAN ($\bar{x}$)	STD DEV (σ)	MEAN +2σ	MEAN -2σ
9-04-82	TSAT	582	-.245	.241	.237	- .727
	TSCT	582	.359	.347	1.053	- .335
9-06-82	TSAT	578	-.428	.889	1.350	-2.206
	TSCT	578	.226	.428	1.082	- .630
9-07-82	TSAT	249	-.194	.129	.064	- .452
	TSCT	249	.268	.287	.842	- .306
9-09-82	TSAT	872	-.229	.441	.653	-1.111
	TSCT	872	.013	.457	.927	- .901
TOTAL	TSAT	2281	-.280	.546	.812	-1.372
	TSCT	2281	.183	.431	1.045	- .679

/NOTE/ TSAT = Total System Along Track Error
TSCT = Total System Cross Track Error

The data shows that TSCT was within the 2.5 nm enroute criteria throughout the test program. TSAT does exceed the 1.5 nm criteria in some instances on flight 9-06. However, the aggregation of alongtrack error over the total test program stays within the +1.5 nm limit as shown at the bottom of Table. 1.3.

The area in which the receiver met or exceed the accuracy requirements of Advisory Circular 90-45A in Alaska are shown in Figure 1.2. This area is defined on the east by the 156°W meridian, on the west by the 168°W meridian, on the south by the 58°N parallel and on the north by the 65°N parallel. The TDL-711 system repeatedly operated within the referenced accuracy criteria in this region. On some occasions the system worked accurately in areas east of the specified region; however, the performance was not sufficiently repeatable in these areas to confidently utilize the system for IFR navigation. Additional testing may permit expansion of the operational coverage area.

Loran-C navigation within the operational area in Figure 1.2 should be checked for accuracy upon signal acquisition, and at regular intervals thereafter. These checks should be made with reference to other aircraft system navigation aids such as VOR, DME and ADF or by visual methods, if conditions permit.

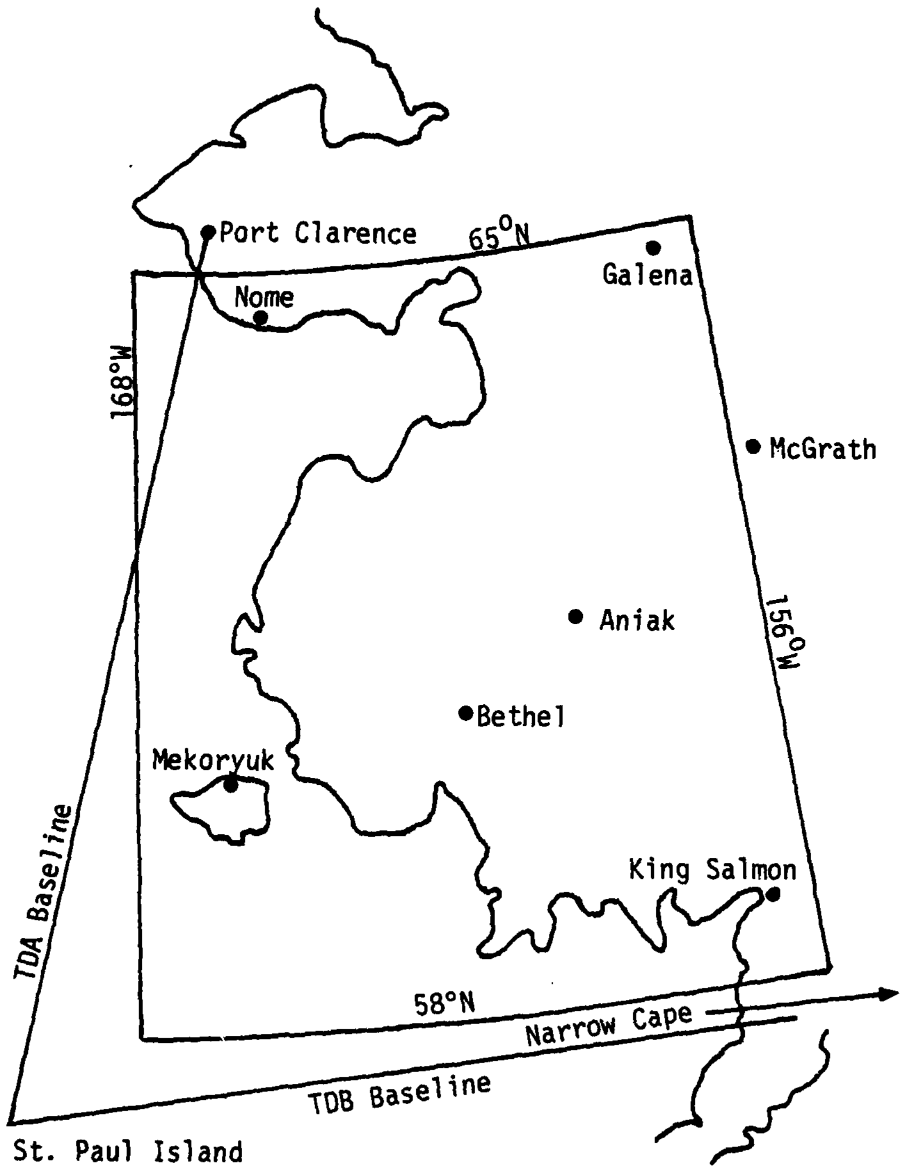

Figure 1.2 Loran-C Operational Area

1.8 CONCLUSIONS

The following conclusions were developed from the flight test of the Teledyne TDL-711 in Alaska:

- Total system alongtrack and crosstrack errors were measured during the Alaska test at times when:
  - Loran-C was used for guidance
  - DME position data was available
  - The Loran-C system acquired and tracked the correct signals

  These errors met Advisory Circular 90-45A criteria at these times.
- Flight technical errors of 0.35 nm (2σ) were measured during the test.
- The TDL-711 system performed very poorly within at least a 60 nm radius of Anchorage. Position errors in excess of 15 nm were not uncommon. System accuracy in the Fairbanks area was also very poor.
- One of the most important problems encountered is that the system can acquire, and track, an erroneous signal and calculate erroneous guidance with no indication to the operator that it has done so. This error is translated into position and guidance error through the coordinate conversion process.
- A second probable source of time difference error observed during the test is propagation modeling error. This error was most apparent when operating near Nome and Kodiak. At these locations the magnitude of the modeling error approached 5 to 6 microseconds. This error in turn produced position error on the order of 0.9 nm at these locations.
- The TDL-711 performed very accurately in the areas around Nome, Bethel, Aniak and King Salmon. The system met or exceeded the enroute accuracy requirements of Advisory Circular 90-45A in the region shown in Figure 1.2.
- The TDL-711 was easy to operate and imposed no undue burden on the flight crew.

2.0 TEST DESCRIPTION AND PROCEDURES

2.1 PURPOSE OF THE TESTS

This document describes the results of a program of the collection of flight test data in Alaska using Loran-C (a wide area coverage navigation system). The purpose of the flight test was to evaluate a Loran-C receiver as an enroute navigation aid in Alaska and to collect data that can be submitted to the FAA in support of an application for a Supplemental Type Certificate (STC). Navigation system errors in alongtrack and crosstrack coordinates were quantified for the Loran-C unit tested (Teledyne TDL-711). Total system crosstrack error, flight technical error and signal coverage data were also quantified in this report. Aircraft position data were obtained from DME multilateration and photographic ground truth systems carried aboard the test aircraft. Included in the test were equipment shakedown flights for the data acquisition system, transition data collection flights and Alaska data collection flights. Data were collected in a format compatible with analysis requirements as described in Section 4.

2.2 TEST OBJECTIVES

The objective of this project was to collect Loran-C performance data in Alaska that would be applicable in the consideration of Loran-C by the FAA as an enroute navigation aid. The specific objectives of this flight test were defined as follows:

- Collect Loran-C data relating to signal coverage and navigation system accuracy in the Alaska enroute structure.
- Collect and analyze Loran-C data while enroute to Alaska.
- Collect and analyze signal information such as propagation errors, signal to noise ratios, etc.
- Collect and analyze fixed site Loran-C data so that signal anomalies can be identified in flight data.
- Qualitatively evaluate the potential for, and the effects of, operator errors using the Loran-C airborne system selected.
- Collect and analyze flight technical error (FTE) data associated with the airborne Loran-C system selected.
- Provide the necessary installation and accuracy data so that a Supplemental Type Certificate (STC) can be issued by the FAA for the Loran-C system tested.

2.3 TEST LOCATIONS

The extensive navigation coverage provided by a limited number of transmitters makes test location selection a complex process in the case of wide area coverage systems. Signal bias errors and even coverage can vary from location to location depending on such factors as local topography, transmitter geometry and localized electromagnetic disturbances. Test locations were chosen to include as many geographi-

cally diverse situations as is possible within the constraints of a flight test.

The overall route of each flight is depicted in Figure 2.1. Major test locations in the Alaska area were:

ANCHORAGE	BETHEL
FAIRBANKS	McGRATH
KOTZEBUE	KING SALMON
GALENA	KODIAK
NOME	AMBLER

In addition, while enroute to Alaska, data were collected when Loran-C signals were available. The transition portion of the flight test is depicted in Figures 2.2 & 2.3. Ten (10) flight legs were flown for the transition portion of the flight test with each leg being approximately 430 nm in length. Most of the legs were terminated with a published RNAV approach at specific locations across the continental U.S.

Navigation system check-out flights and pilot training flights were conducted in the vicinity of Palm Beach International Airport in West Palm Beach, Florida. Calibration of the data acquisition system was also conducted in the Palm Beach area utilizing visual reference data and DME cross correlation.

2.4 STC APPLICATION

One of the objectives of this flight test program was to apply for a Supplemental Type Certificate (STC) on the TDL-711 Loran-C navigator in the Alaska Region. The ultimate goal of these tests is certification of the TDL-711 for IFR navigation in those areas of Alaska where it is reliable and meets AC90-45A airspace requirements. This report will serve the purpose of presenting the necessary accuracy data to the FAA so that the airspace in which the TDL-711 can be used in IFR conditions can be determined.

The application for the issuance of a Supplemental Type Certificate (STC) required close coordination with the appropriate FAA Regions involved. The installation of the TDL-711 system was accomplished at the aircraft's home base in West Palm Beach, Florida. For this reason the application for the STC was filed through the Southern Region. The Southern Region was responsible for processing the application, conducting the conformity inspection and issuing the Type Inspection Authorization (TIA). The Alaskan Region was responsible for observing the flight test portion of the project and assuring that all of the necessary items on the TIA were satisfied. FAA personnel in the Alaskan Region participated in approximately half of the flights flown in Alaska. The procedure for obtaining a STC is outlined in Figure 2.4. The contractor was responsible for submitting the necessary paper work for the flight tests and conformity inspections.

The items necessary to pass this inspection process are as follows:

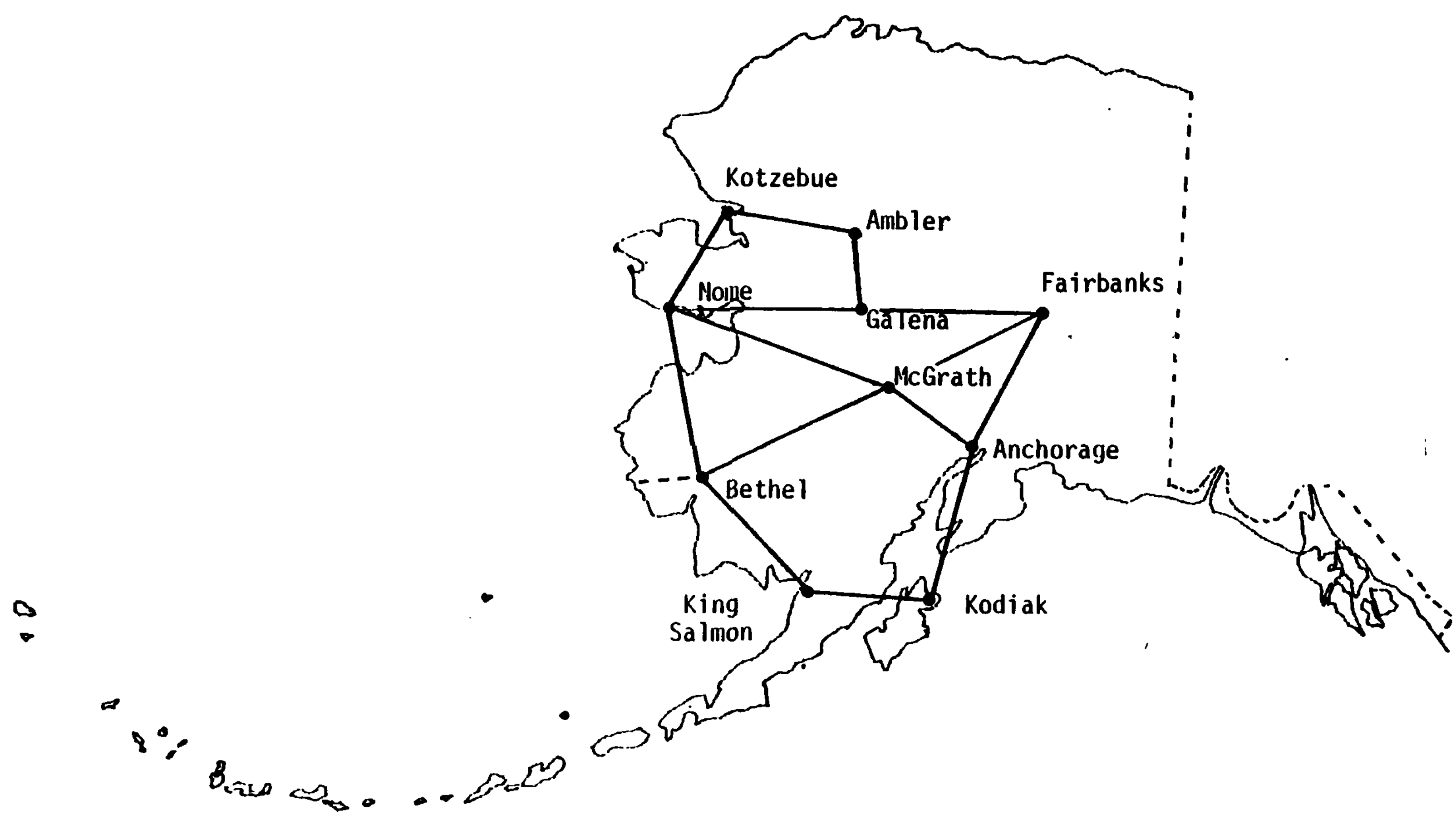

Figure 2.1 Alaska Loran-C Flight Test Routes

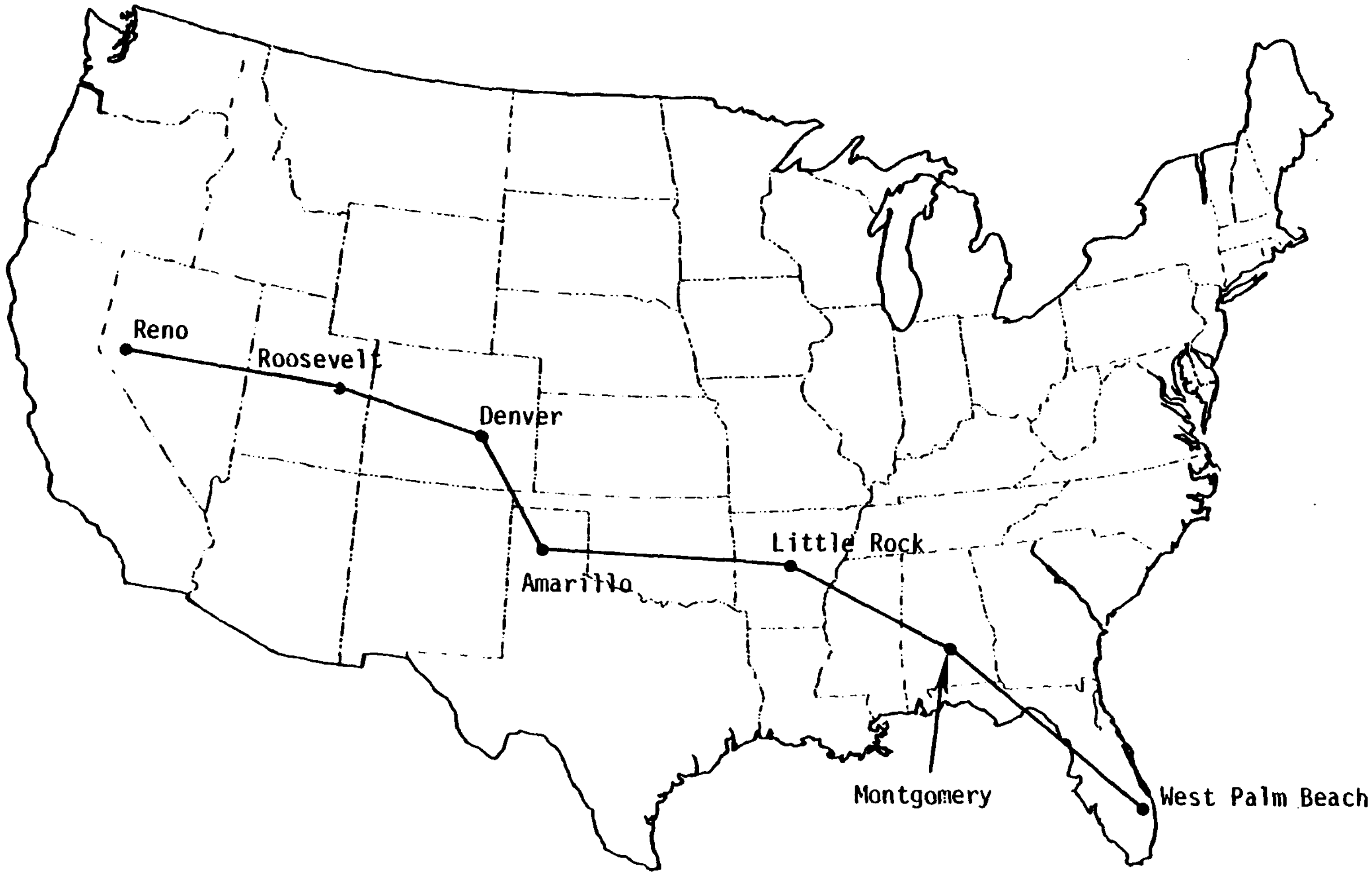

Figure 2.2 Transition Flight Test Route (W. Palm Beach to Reno)

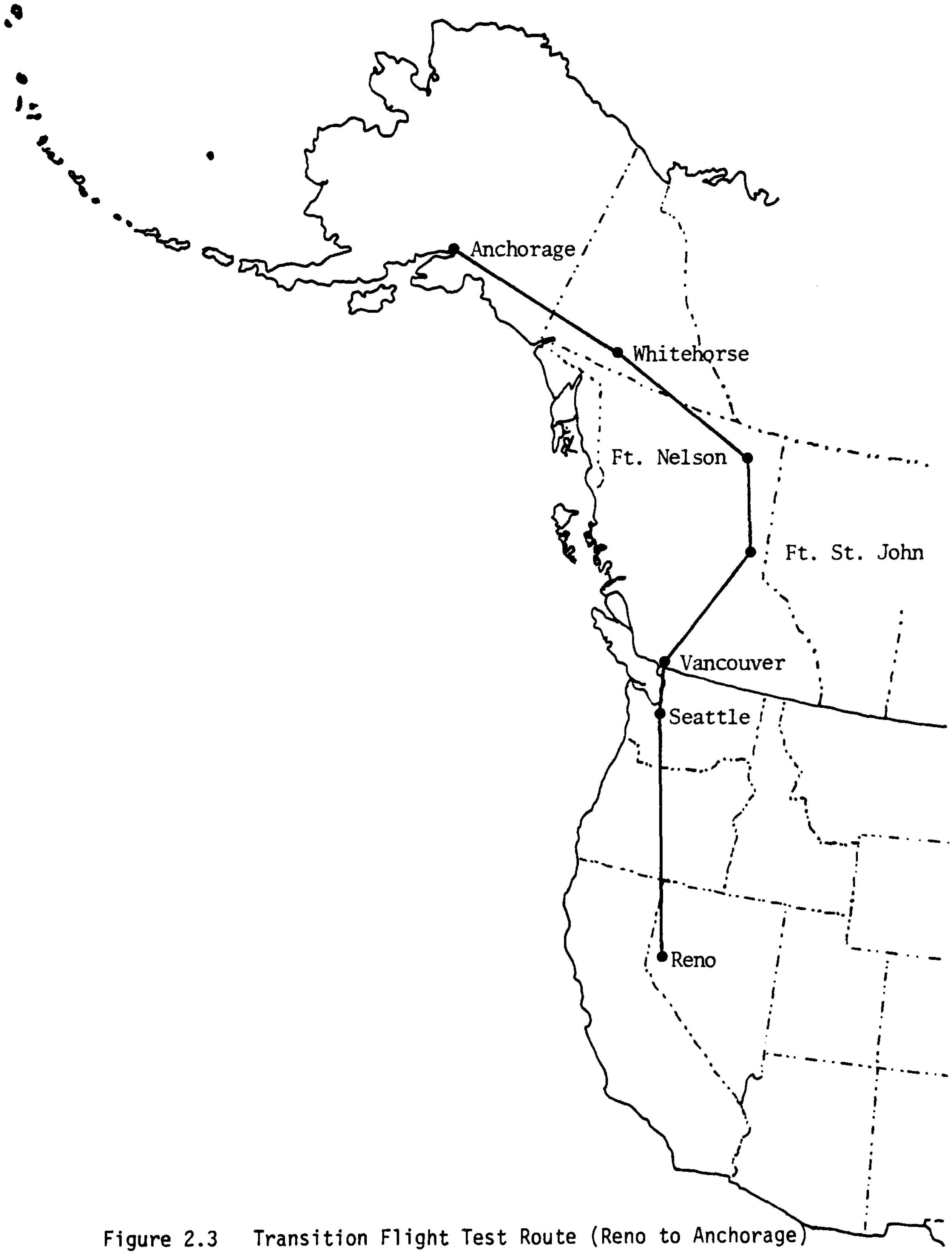

Figure 2.3 Transition Flight Test Route (Reno to Anchorage)

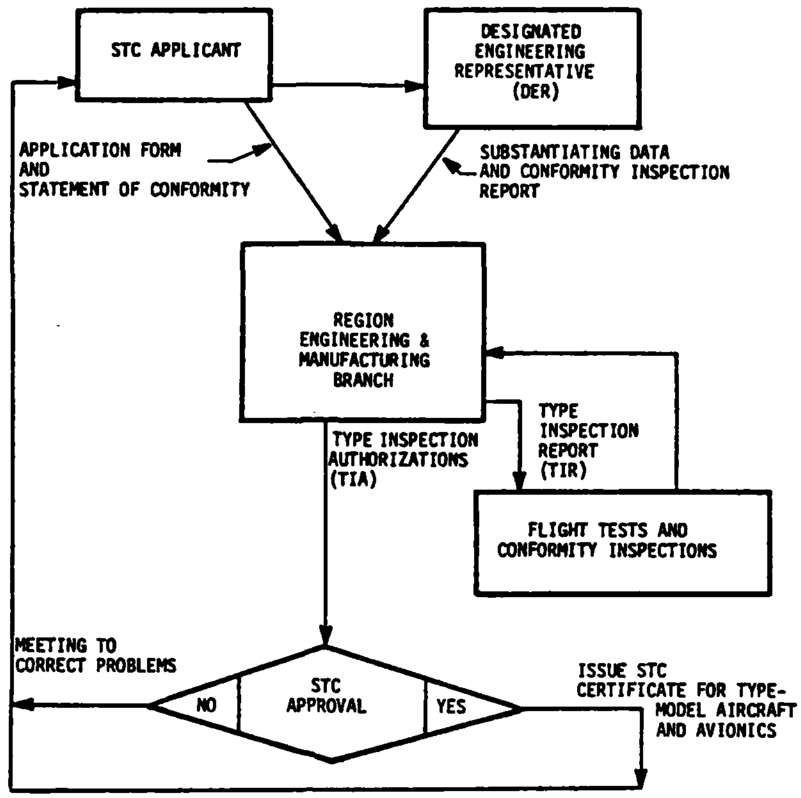

Figure 2.4 Process Leading to a Supplemental Type Certificate[1]

Conformity Inspection

- Loran-C Receiver (TDL-711) certified to conform to AC90-45A
- Installation Drawings (reproducible) with instructions
- Stress Analysis on airframe holes
- Wire type, bolt type, etc.
- FAR 23-G loading analysis or pull test
- If desired, the necessary paper work to receive a supplement to the aircraft flight manual

Flight Tests

- Detailed test plan
- System accuracy in alongtrack and crosstrack coordinates
- Method of Loran-C accuracy verification (DME multilateration, photography)
- Geographical location
- Any other previous Loran-C flight test reports and applicable data

After the issuance of the original STC, issuance of another STC is very straightforward as outlined in Figure 2.5.

The following sections will describe the flight procedures and the test routes flown both in the Alaska region and during the transition phase of the flight test.

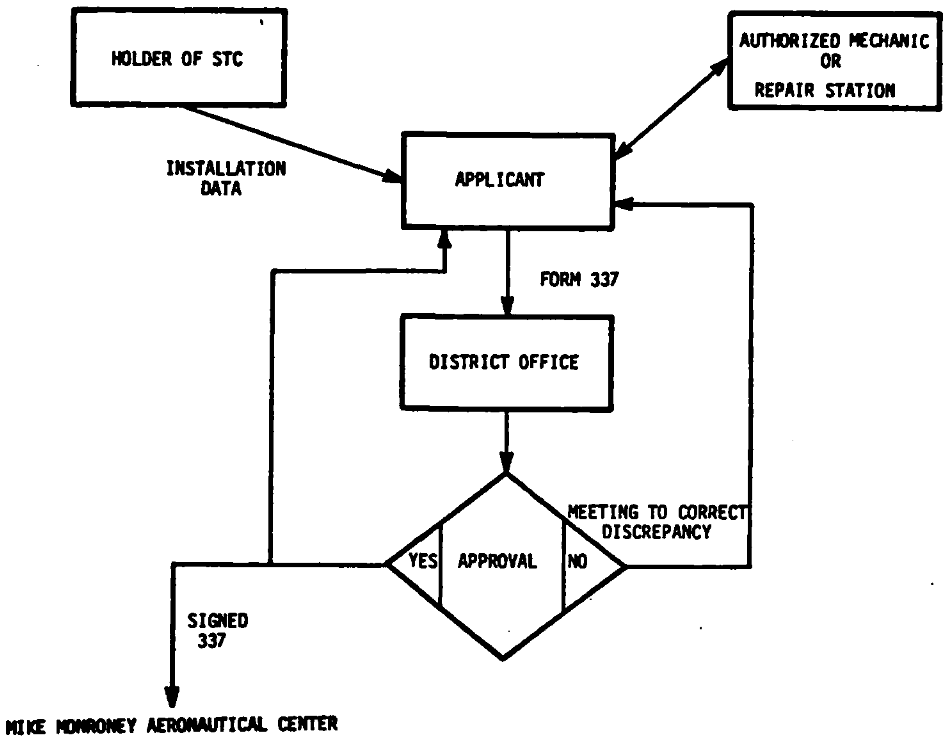

Figure 2.5 Procedure After Issue of Original STC[1]

2.5 FLIGHT TEST ROUTES AND PROCEDURES

In this section the Alaska phase and the transition phase of the flight test program are discussed in detail. In order to decrease the number of ATC directed course deviations, virtually all enroute segments followed the Victor airway structure and most planned approach segments were published RNAV approaches. Accuracy data were collected whenever the ground truth system was operational and planned flight altitudes were chosen to maximize line of sight DME reception. A discussion on the operational status of the DME ground truth system is contained in Section 4.2.1.

2.5.1 Alaska Flight Test Routes and Procedures

A total of 6,300 data miles were flown in the State of Alaska during a period from September 1, 1982 to September 10, 1982. The following section will describe in detail the Loran-C flight test routes and procedures flown in Alaska. The aircraft was based in Anchorage, AK and was stationed at the FAA hanger on the airport.

In order to meet the major objective of obtaining a STC for the TDL-711 Loran-C receiver, the specific objectives of this flight test were defined as follows: (1) determine usable accurate signal coverage, and (2) determine avionics accuracy within that coverage. The test routes were concentrated in the southwest part of the state where there

is published coverage from the North Pacific Loran-C chain. Typically, single triad coverage was available from the Master Station at St. Paul (in the Pribilof Islands) and the secondary stations at Port Clarence and Narrow Cape. The other secondary station in the chain at Attu Island was utilized only as a backup station. Little overland coverage was available from the Gulf of Alaska chain according to published charts (see Figure 2.6).

WORLDWIDE LORAN-C COVERAGE

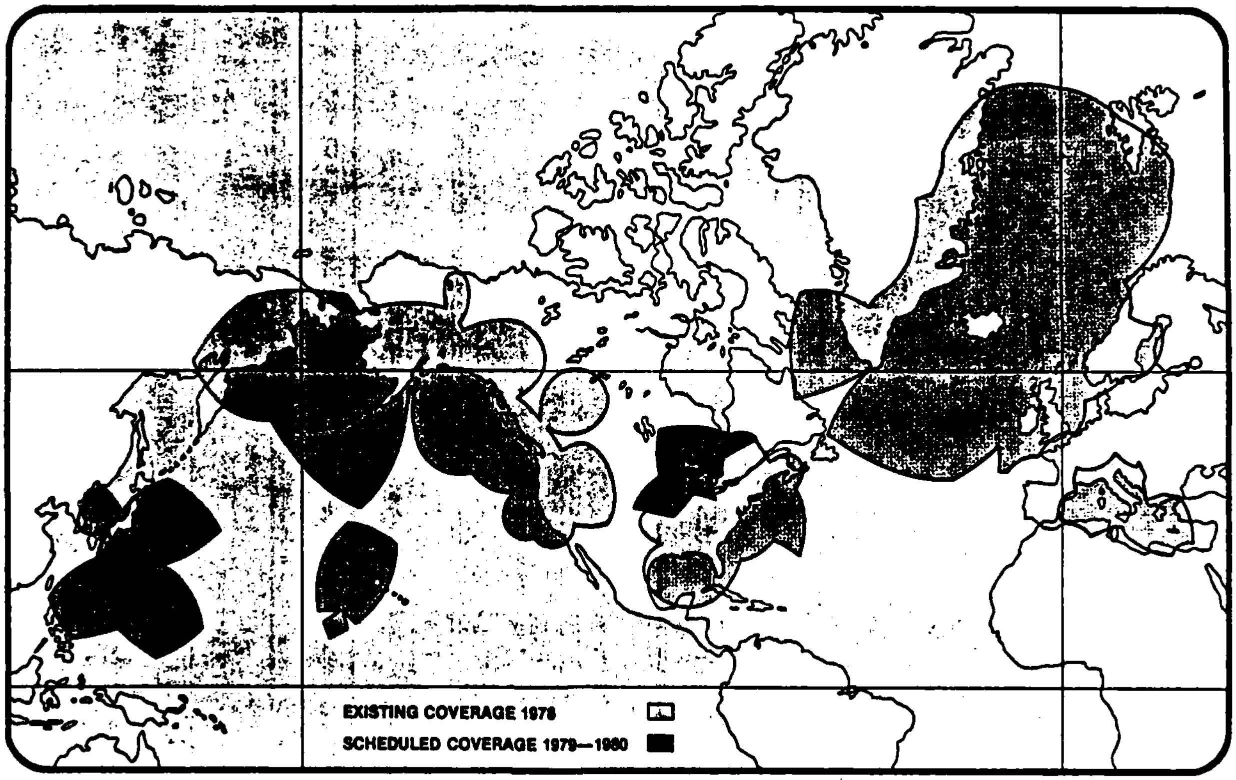

Figure 2.6 Predicted U.S. and Alaska Loran-C Coverage [2]

Accuracy data was collected whenever the ground truth system was operational (minimum of two DME stations and good geometry). In those cases were DME coverage was poor (west of Bethel) the photographic ground truth system was utilized.

To demonstrate compatibility with the existing VOR/DME system and air taxi operator routes, all of the flight test routes were along published, low altitude airways in the Southwest area. The Alaska Loran-C flight test program consisted of an area roughly defined by Anchorage, Fairbanks, Nome, Kodiak and McGrath (see Figure 2.1). Three basic flight test routes were flown. Test route 1 consisted of 3 segments

while test routes 2 and 3 consisted of 4 and 5 segments, respectively. Each leg was approximately 430 nm in length (2.9 flight hours). These legs consisted of enroute segments only. Segments were identified by the following number system.

ROUTE #	SEGMENT	ORIGIN	DESTINATION
	1	Anchorage	Nome
1	2	Nome	McGrath
	3	McGrath	Anchorage
	4	Anchorage	Galena
2	5	Galena	Nome
	6	Nome	King Salmon
	7	King Salmon	Anchorage
	8	Anchorage	King Salmon
	9	King Salmon	McGrath
3	10	McGrath	Galena
	11	Galena	Nome
	12	Nome	Anchorage

The route structure and segments were designed so that most segments were flown at least twice while others were flown three and four times.

An additional flight was flown west of Bethel area as depicted in Figure 2.7. The purpose of this segment was to explore overall signal accuracy and coverage and to demonstrate operations similiar to those normally made by local air taxi operators. As mentioned earlier, photographic data were collected to verify the accuracy of the Loran-C navigator in this area.

Enroute segments included flight over a variety of topographic and geographic conditions. Availability of DME transmitters along the route was adequate for data acquisition at flight altitudes in the range of 10,000-12,000 feet.

In addition to the enroute segments flown in the Alaska area, five Loran-C RNAV approaches were accomplished. The approaches, with the exception of Anchorage, were flown in an ad hoc manner, that is they were executed without the aid of approach plates or published procedures. Typically the approaches were flown utilizing two waypoints, the runway threshold and the FAF (Final Approach Fix) waypoint located five nautical miles out on centerline. Five approaches were executed in total at the following locations:

Anchorage	Nome
Bethel	King Salmon
Fairbanks	

In addition to the requirements of the ground truth system, Loran-C coverage considerations also contributed to the development of the flight test route. The areas of reduced accuracy were somewhat predictable.

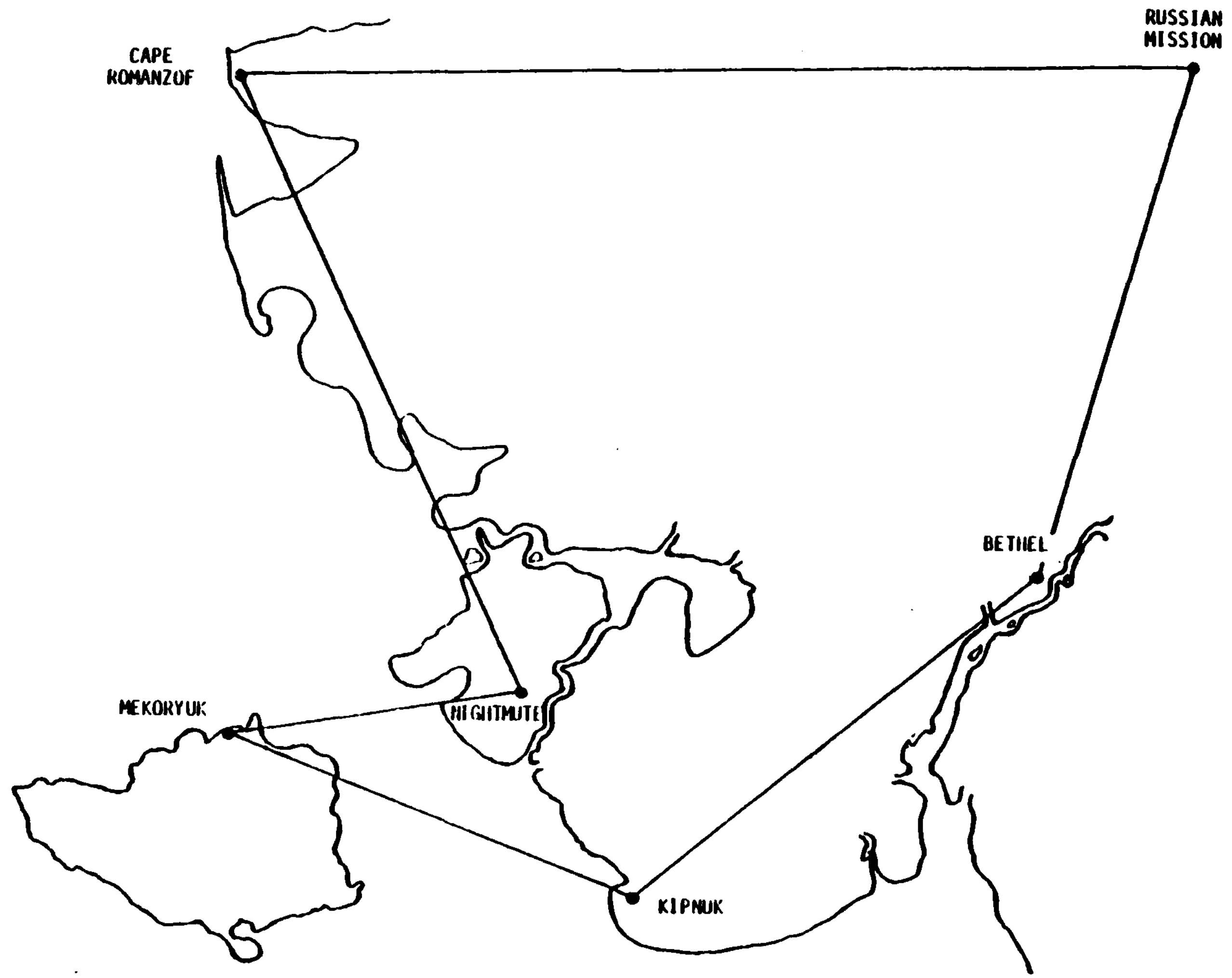

Figure 2.7 Bethel Spur Route

The route of flight for this test was selected to include areas of both good geometry and bad geometry.

2.5.2 Transition Flight Test Rotues and Procedures

The transition portion of the flight test program consisted of an area roughly defined by West Palm Beach, Florida; Denver, Colorado; Reno, Nevada; Vancouver, British Columbia; and Anchorage, Alaska (see Figures 2.2 & 2.3). Ten (10) flight legs were flown for the transition portion of the flight test with each leg being approximately 430 nm in length (2.9 flight hours). These legs consisted of departure, enroute and approach segments. Segments were identified by a number as follows:

Segment		
1	West Palm Beach, Florida	Montgomery, Alabama
2	Montgomery, Alabama	Little Rock, Arkansas
3	Little Rock, Arkansas	Amarillo, Texas
4	Amarillo, Texas	Denver, Colorado
5	Denver, Colorado	Roosevelt, Utah
6	Roosevelt, Utah	Reno, Nevada
7	Reno, Nevada	Seattle, Washington
8	Seattle, Washington	Fort Nelson, Br. Columbia
9	Fort Nelson, Br. Columbia	Whitehorse, Yukon
10	Whitehorse, Yukon	Archorage, Alaska

In this section the transition flight route and the approach procedures will be discussed. Finally, a qualitative evaluation of the adequacy of DME ground truth coverage in each of the terminal areas is discussed.

Ten transition enroute segments using airway turnpoints were flown during this flight test. Each segment was flown twice, once in transition to Anchorage, AK and once on the return flight to West Palm Beach, FL. The transition portion of the flight to Alaska was flown during a period from August 29, 1982 to September 1, 1982. The return portion of the flight was flown from September 17, 1982 to September 21, 1982.

Enroute segments included over water, coastal plain, central plain and Rocky Mountain overflight. Availability of DME transmitters along the route was adequate for data acquisition at flight altitudes in the range of 10,000-12,000 feet.

In addition to the requirements of the ground truth system, Loran-C coverage considerations also contributed to the development of the flight route. Loran-C signals are generally limited to about an 800 nm range over land. Additionally, Loran-C suffers from an anomaly known as baseline extension degradation where position accuracies are reduced in certain areas based on transmitter geometries. The areas of reduced accuracy are predictable in nature and the route of flight for this test was selected to include areas of both good geometry and bad geometry. For example, the Denver, Colorado area was selected because it is on the outer fringe of current Loran-C coverage.

Error data were collected at all times during transition enroute operations and were analyzed as to project applicability during the analysis phase by reference to the inflight log maintained by the observer. Flight route deviations did occur due to weather constraints; however, these deviations were evaluated as to test result applicability. Data collected during this flight test represent a comprehensive baseline data base of both flight technical error and navigation system error values over a variety of topographic and geographic conditions.

In addition to the transition enroute data collected during this flight test, a limited amount of approach data were collected. An RNAV non-precision approach using information from the Loran-C system being tested was attempted at the termination of each segment. During the portion of each approach that multiple DME coverage was adequate for operation of the data acquisition ground truth system, approach phase navigation system error values were determined. Low altitudes during the final phases of the approach, in most cases, limited the availability of adequate DME coverage. However, FTE data was collected during the entire approach phase in all cases.

Eleven approaches were completed at eight different airports during the transition phase of the Loran-C testing. All of the approaches were published RNAV approaches with the exception of Anchorage International approach. Although sixteen approaches were planned in total during the transition phase, it was only possible to complete eleven of the sixteen due to weather constraints and traffic conditions at certain airports. The eight approach locations were as follows:

1) Palm Beach Int'l; West Palm Beach, Fla; RNAV Rwy 13
2) Dannelly; Montgomery, Ala; RNAV Rwy 3
3) Adams; Little Rock, Ark; RNAV Rwy 22
4) Tradewind; Amarillo, Tex; RNAV Rwy 35
5) Jeffco; Denver, Colo; RNAV Rwy 29R
6) Roosevelt Mun; Roosevelt, Utah; RNAV Rwy 25
7) Reno Int'l; Reno, Nevada; RNAV Rwy 16
8) Anchorage Int'l; Anchorage, AK; RNAV Rwy 6R

Although every effort was made to select those destination RNAV approaches most likely to supply DME signal sources required by the data acquisition system, primary emphasis was placed on selecting terminal locations which were indicative of a variety of navigation system transmitter geometries, and potential signal propagation effects. It is felt that the route and destinations selected for this flight test represented the greatest variety of signal variations available.

2.6 FLIGHT CREW

Three subject pilots were utilized for this test effort. All of the pilots were commercial and instrument rated, and all had previous experience flying long range navigation equipment. Table 2.1 presents a breakdown of the flight hours and qualifications for each pilot.

Table 2.1 Project Pilot Experience

PILOT	TOTAL TIME	COMM.	INST.	ATR	PREVIOUS LONG RANGE NAV. EXP.
A	35,000 hrs	✓	✓	✓	Omega
B	35,000 hrs	✓	✓	✓	Omega
C	2,000 hrs	✓	✓		Loran-C

All enroute and approach segments were flown by the primary subject pilot. The copilot acted as safety observer and was also responsible for ATC communications and data entry into the TDL-711 Loran-C system. The flight test observer was tasked with operation of the data acquisition system and the manual logging of unusual flight situations, such as deviation due to weather or ATC requests.

3.0 TEST VEHICLE AND EQUIPMENT

3.1 TEST AIRCRAFT

The test aircraft chosen for these flights was a Beechcraft Queen Air 65. This vehicle was chosen for its economy, large cabin space and gross weight payload capability. Data acquisition equipment was well within maximum gross weight limits with a full load of fuel, full crew and required test support personnel. Aircraft range as currently configured is approximately 6 hours plus reserve. All flight legs were planned to be approximately 4.5 hours in length leaving an adequate reserve.

The Queen Air is currently leased by Systems Control Technology, Inc. and was dedicated to this program during the data collection segment of the flight test schedule. The subject pilots were familiar with the operation of this aircraft, reducing the need for additional pilot familiarization flights. The aircraft is equipped with an EDO Century III autopilot system, a Collins FD-105 flight director system, dual communications radios, dual VOR navigation radios, KNC-610 RNAV system and an altitude encoding transponder. VOR/DME navigation system outputs were displayed on the FD-105 flight director system consisting of a horizontal situation indicator (HSI) and attitude direction indicator (ADI) with a command steering display. During the data collection activity, a dedicated course deviation indicator (CDI) display was utilized to display Loran-C steering commands at all times. The safety observer monitored aircraft position by conventional VOR navigation using a standard CDI display on the right side of the front instrument panel. The TDL-711 control display unit was mounted in the center console between the two pilots.

The aircraft was equipped with static wicks manufactured by TCO Manufacturing, Inc. Three wicks were installed on each control surface which provided more than the adequate number of static discharge points. The static wicks are very lightweight and designed to discharge static in the 100 KHz range.

3.2 TELEDYNE TDL-711 LORAN-C RECEIVER/PROCESSOR

The Loran-C airborne system used for the flight test program was a Teledyne TDL-711 micro-navigator system consisting of an E-field vertical antenna; a receiver/computer unit mounted on the data acquisition rack; a control display unit (CDU) mounted on the aircraft's center console; and a CDI in the center of the pilot's instrument panel to display Loran-C course deviation.

The control display unit, shown in Figure 3.1, is the operator's interface with the Loran-C system. It displays position information both in latitude/longitude and time differences; shows which waypoint, or waypoint pair, has been selected; displays all navigation and test modes; and shows the information being entered through the keyboard.

There are six decimal points for use with the data shown in each upper display window (two of the six in each are shown in Figure 3.1).

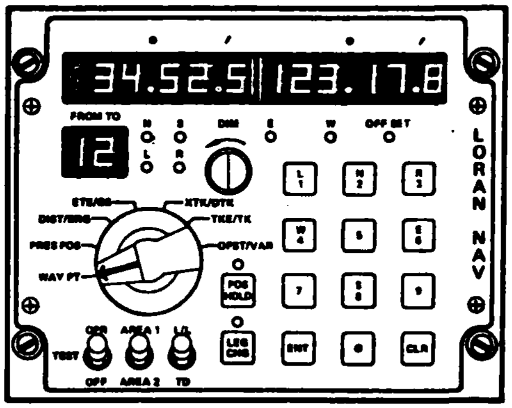

Figure 3.1 TDL-711 Control Display Unit [2]

These same decimal points are also used to warn the crew of non-standard Loran-C system operation. All the decimal points blink when the processor is operating in the master independent mode (the master signal is unusable or non-existent and a third secondary has been added to the computations, with one of the secondaries selected as master). They remain on steadily when navigation information (and thus, the computed position) is unusable.

The rotary data selector switch chooses the information to be displayed:

- "WAY PT": the selected waypoint position is displayed, or the coordinates to be entered for the selected waypoint are shown
- "PRES POS": position displays present position or allows entry of present position
- "DIST/BRG": displays, in the left and right windows, range and bearing to the selected "TO" waypoint in the "FROM-TO" window
- "ETE/GS": the processor shows time to go to the "TO" waypoint and present ground speed
- "XTK/DTK": shows crosstrack distance on the left and desired track angle on the right
- "TKE/TK": displays track angle error and track angle
- "OFST/VAR": shows the current parallel offset distance (or allows selection of a new offset), and lets the operator either see the current magnetic variation, if any, or enter a new variation.

The "MODE SELECTOR", (lower left corner) is a three position switch which, at the operator's discretion, either shuts off power to the system, initiates the self-test sequence, or puts the system into normal operation.

One of two pre-programed coverage areas can be chosen with the area switch.* This switch selects the triad (a three-station set of master and secondaries) which is to be used for position computation and

/NOTE/ *This particular Loran-C unit was modified with Teledyne's 16 triad option.

navigation. All of the Programmable Read Only Memory (PROMs) for all test coverage areas were available in the system. The "L/L-TD" switch chooses the mode of the selected position display or entry - latitude/longitude or time differences.

Pressing the "POS HOLD" switch stores the aircraft's present position at the moment it is depressed. If the rotary data selector is in the "PRES POS" mode, the displays will freeze. In any event, position continues to be updated once per second. The indicator light stays on until the switch is pressed a second time.

To effect a leg change, the "LEG CHG" switch is depressed an the next waypoint pair is entered using the keyboard. On the TDL-711, the leg change light will flash when the "TO" waypoint has been reached, and the new waypoint "FROM-TO" pair must be entered manually. There is no automatic leg change function. The selected waypoint pair appears in the "FROM-TO" window.

The keyboard is for information entry. Certain keys have double functions depending on the position of the rotary data selector switch. The "ENT" key inserts the keyboard entry into the processor. The "CLR" key is used to clear keyboard entry errors.

The "N" and "S" lights indicate latitude, and the "E" and "W" longitude. Whenever an offset course has been entered, the "OFFSET" light remains on.

When the aircraft is left or right of desired track, when the track angle error is left or right of desired track heading, or when the offset course is left or right of nominal, the "L" or "R" lights will be on the show the direction of displacement.

The "DIM" control regulates all CDU lights except the "OFFSET", "LEG CHG", and "POS HOLD" indicators. They are controlled with the cockpit dimmer controls.

Certain internal diagnostic functions can be summoned with coded key entry sequences.

The output of the Loran-C navigator drives a deviation indicator (CDI), giving linear deviation from the selected "TO" waypoint course. Full scale deflection left or right of center is 1.28 nautical miles. The "TO" flag indicates that the aircarft is located short of the "TO" waypoint. The "FROM" flag indicates a position beyond the "TO" waypoint. The red "NAV" flag indicates that steering commands are invalid.

The Loran-C receiver is designed to run a remote display unit (RDU), and the information it provides to that remote display can be externally programmed through the PROM.

3.3 REFERENCE SYSTEMS

3.3.1 Multiple DME Positioning System

The multiple DME positioning system used was a Rockwell-Collins DME-700. The DME-700 transmits pulsed signals to a ground station and receives responses from the station. Slant range is determined by measuring the transmit time from the aircraft to the station and back to the aircraft. The DME-700 is capable of operating in several modes including: standby, single channel, diversity, and scan (which was utilized for the purpose of this test). The scan mode provides a capability to service up to five stations at a high rate, and can scan the other 274 channels for valid replies at the same time. The DME-700 receives serial digital control information on one of two ARINC 429 input data buses. The control information also instructs the DME as to what mode of operation to use. The DME-700 delivers serial digital distance data over two ARINC 429 output data buses. DME data (distance and frequency) from the five closest DME stations are transmitted via the data output buses at 3.5 sec intervals. Depending on the number of stations, received data from an additional 15 (fifteen) DME stations can also be transmitted via the data output buses.

3.3.2 Photographic Positioning System

The photographic positioning system used was a Minolta X-700 camera system. The Minolta X-700 is a 35 mm Single Lens Reflex (SLR) camera system. Options available for the X-700 system that were utilized for this flight test program are as follows:

- Multifunction back
- MD-1 Motor Drive
- Remote Control

The multifunction back allows the user to imprint on each negative one of several items: time (hours, minutes and seconds), calendar date (month, day and year) or it can be programmed to number each negative in sequence from 1 to 999,999. For this flight test application the time option was utilized. This allowed the data to be time correlated with the airborne system data collector. The motor drive and remote control options allowed the flight test engineer to operate the camera while observing other necessary data collection parameters.

The camera was mounted inside the aircraft pointing through the bottom of the fuselage. Two lenses were used (35 mm and 70 mm), depending on the altitude above the ground, to yield a reasonable field of view. Photographs were taken of airport runways and VOR stations so that an accurate indication of actual aircraft position could be determined. Photographs were developed on site to insure the validity and quality of the data. Details of how the aircraft's position was determined are discussed in Section 4.0.

3.4 DATA ACQUISITION AND RECORDING SYSTEM

The data acquisition package utilized during the flight test program consisted of eight major components. They were as follows:

- MFE 452B w/424 PAR Cassette Recorder
- Collins DME-700
- Microcomputer Chassis, Logic and Interface Boards
- Keyboard and Alphanumeric Display
- Loran-C Receiver Processor Unit (RPU)

The appropriate data parameters were digitally recorded on the MFE 452B with 424 PAR option cassette recorder. These data were recorded from three distinct sources via the microcomputer logic and interface boards. The three sources were as follows: Collins DME-700, analog voltages representing aircraft systems and the Teledyne TDL-711 system RPU. The operator/system interface components consisted of a keyboard, alphanumeric display and a CRT console, to be used for post-flight quick-look data dumps. The primary power for the data acquisition system was 28 VAC.

3.5 SYSTEM CHECKOUT AND CALIBRATION

The Loran-C navigation system and the airborne data acquisition system were checked out in a series of calibration flights in the West Palm Beach area prior to beginning flights for data collection. At the same time, the crew utilized the navigation equipment and became proficient in its operation. The training series consisted of local enroute flights and approaches.

Operational validation and calibration of the ground truth and data acquisition system was accomplished in the West Palm Beach area. The calibration flights consisted of two phases: an enroute test phase (approximately two hours) and a local area transition phase (approximately one hour). Automatic DME selection functions were tested as well as the accuracy of the multilateration ground truth system.

Total flight time required for the familiarization/calibration tests was approximately four hours. Operationally, the calibration test were conducted using the procedures and guidelines laid down for the overall flight test.

4.0 DATA PROCESSING AND PROCEDURES

The data obtained during the flight test consisted of digital data recordings on magnetic tape, photographic data at selected sites and observations of the pilots and flight test observer. The digital data recording system, used in the test, recorded three generic types of navigation and aircraft system data. These types were:

- analog voltage or phase angle data
- DME digital data
- TDL-711 Loran-C digital data

All data were time tagged by the data collector clock to the neareast .01 second. Data were recorded at a 1Hz rate on magnetic tape cassettes. On the transition flight from West Palm Beach to Anchorage, data were recorded at periodic intervals of approximately five minutes on line and five minutes off line. During the Alaskan flight testing and the return flight to West Palm Beach data were recorded continuously. In all, 120 cassettes of test data were obtained. Due to the large amount of data, processing was performed at a 0.1 Hz rate thereby providing data at ten second intervals.

All flight test data were processed with the contractor's microcomputer system. The system consists of a North Star Horizon microcomputer system controlled by a Zilog Z-80 microprocessor. The system has four 5.25 inch floppy disk drives, a line printer, a digitizer tablet, and a small, flatbed incremental plotter.

All digital data were transmitted from the test data recorder to the North Star computer and stored on floppy disks. Data processing programs were written in North Star Basic or Z-80 Assembler.

4.1 CHARACTERISTICS OF THE DATA

The following analog data were recorded during the test and utilized in the data reduction procedure:

- dynamic presure (indicated airspeed)
- altitude reference } potentiometer voltages
- altitude wiper }
- aircraft heading synchro
- CDI indicator voltage
- CDI flag voltage

Each of the analog channels was calibrated in the contractor's laboratory and in ground tests installed in the aircraft. In addition, the flight test observer manually recorded altitude and airspeed gauge information at approximately twenty-five points during flight. These data points were used to fine tune the indicated airspeed and altitude equations.

Seven DME data channels from the Rockwell-Collins DME-700 were obtained each second. Each channel contained a time tag, co-channel VOR

frequency and DME distance. In areas where there were five or more DME stations available, the DME-700 provided DME measurements from five separate stations. The additional two channels contained data from two of the five channels taken about a half second later. When fewer than five stations were available, the DME-700 provided repeated measurements from the available stations to complete the seven channels of data.

The TDL-711 Loran-C navigator was equipped with a specialized PROM for providing a considerable amount of Loran-C receiver information through the remote display unit (RDU) data line. The Loran-C information is divided into three general categories; display replica data, Loran-C signal processing data and Loran-C navigation data. Specific parameters recorded in these categories are:

Display replica data

- CDU annunciators
- left hand digital display
- right hand digital display
- from/to waypoint display
- decimal points and other CDU lamps
- distance to waypoint register for display
- ground speed register for display
- CDU mode switch selector position

Loran-C signal processing data

- time difference A
- time difference B
- Loran-C track status
- Loran-C signal to noise ratio
- Loran-C station blink status
- Loran-C envelope detection status
- Loran-C envelope numbers
- triad in use
- group repetition interval's (GRI's) per CDI update

Loran-C navigation data

- Loran-C latitude and longitude
- crosstrack error
- to/from waypoint numbers
- to/from waypoint latitude and longitude
- parallel offset value
- magnetic variation value
- CDI scale factor

All Loran-C data were recorded at a 1 Hz rate and were time tagged to the nearest .01 seconds.

4.2 GROUND TRUTH DATA PROCESSING

The ground truth data processing consisted of two tasks. The first was converting the DME measurements from the DME-700 into aircraft

position. The second task was determining aircraft position from the photographs taken with the Minolta X-700.

4.2.1 DME Processing

The processing of the DME information to determine aircraft position was the most time consuming aspect of the data processing. The major elements of the procedure are shown in the block diagram in Figure 4.1.

The procedure begins by providing an initial estimate of the aircraft's position. This was generally provided by using the latitude and longitude coordinates of the nearest VOR facility or an airport reference point. Next, the DME information is read from the floppy disk containing the test data. The DME frequency (or more correctly, the VOR co-channel frequency) is used to identify the station being received. A data file of DME stations, their coordinates, altitude, magnetic variation and their co-channel VOR frequency is maintained for this purpose.

The aircraft position estimate and the DME station coordinates are used to compute a corresponding DME distance. A spherical earth model with the Andoyer-Lambert correction formula for earth oblateness was utilized for this purpose.

The recorded DME distance is corrected for the slant range error and compared with the computed DME distance. The difference is called the DME residual error. The residual error is passed to a mean square estimator of northing and easting corrections. Details of the estimation procedure are contained in Appendix A.

If the easting and northing corrections to the position estimate are sufficiently small, the aircraft position estimate is conditionally accepted as the aircraft's true position. The criteria used for acceptance is:

$$|\Delta \text{ East}| + |\Delta \text{ North}| < .01\text{NM}$$

where ΔE is the easting correction

ΔN is the northing correction

The condition on the acceptance of the point is that the root mean square value of the sum of the residuals be less than some threshold value. For these tests the threshold was set at 0.15 NM, which is 10% of the alongtrack error criteria set forth in Advisory Circular 90-45A. When Loran-C is measured against position fixes from the DME system which meet this criteria, the DME position error will contribute negligible error with reference to AC 90-45A criteria.

If the aircraft position is accepted, the data are placed in an output file for future use in the analysis of Loran-C accuracy. Furthermore, the coordinates are used to compute an estimate of wind. The aircraft's next position estimate for the next record time (usually 10 seconds later) is made from heading, airspeed and wind values by

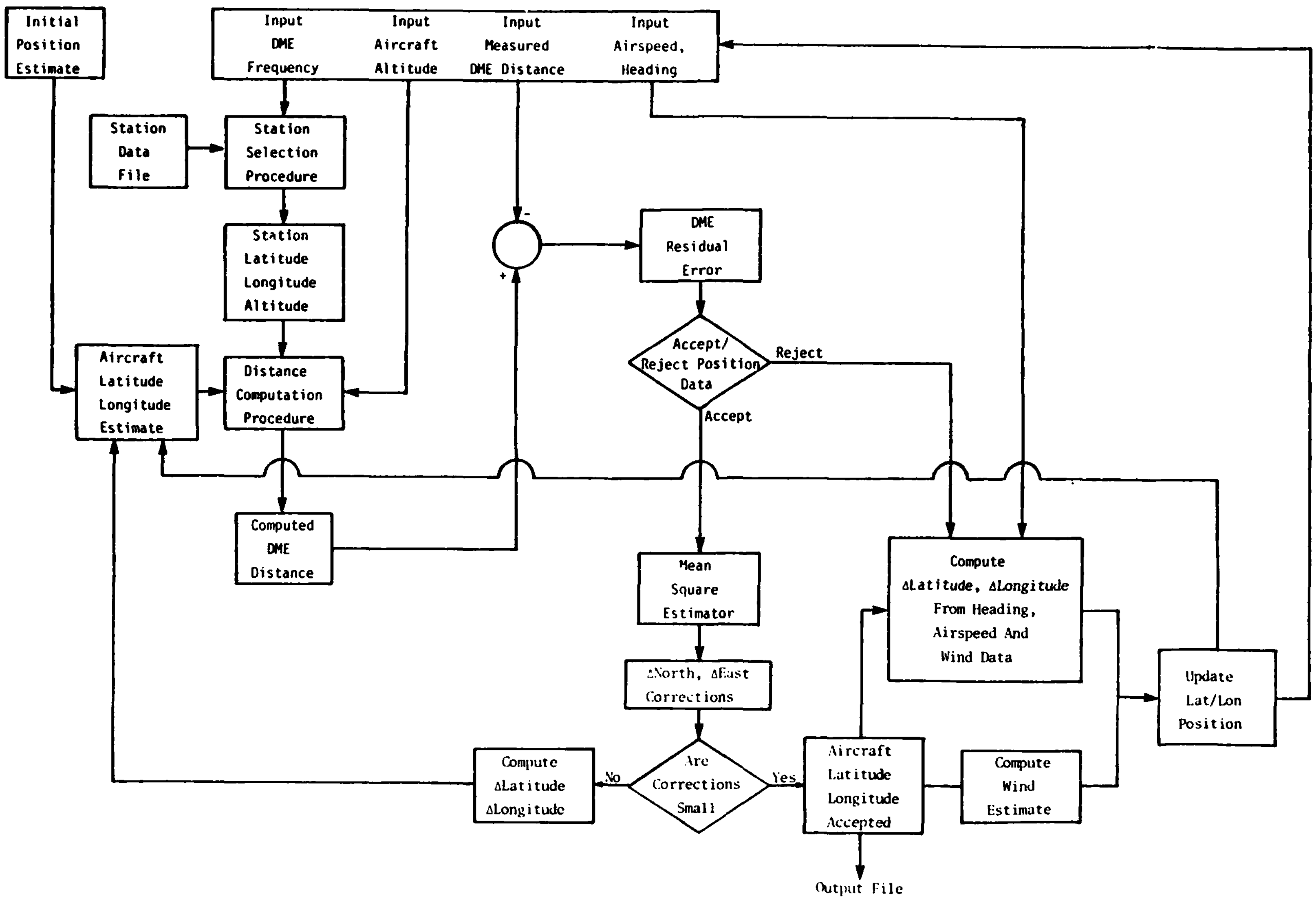

Figure 4.1 DME Positioning System Block Diagram

using dead reckoning procedures. If the point is rejected for any reason, the original aircraft position estimate is updated by dead reckoning to the next record time and the procedure is repeated.

In addition to the residual criteria, the DME data must pass four additional tests. These are:

- a sufficient number of DME stations
- a theoretical position fix accuracy (DRMS value) which exceeds the 0.15 nm threshold
- the correction procedure had to converge in 20 or less iterations
- the denominator of the least square estimator had to be non-zero.

An expression for the theoretical position fixing accuracy (or DRMS) of the DME system is contained in Appendix A.

4.2.2 Photographic Data Processing

To automate the photographic data recovery and reduce both the manual effort and the inherent potential for error, a digitizer tablet was used. Interfaced with a computer and using X-Y coordinates, the tablet allows direct entry of a broad range of data types (graphs, plans, maps, photographs, etc.) with a high degree of resolution. This technique was used with an enlargement (i.e 5x7, 8x10, etc.) of selected frames of film data.

Exact registration with the tablet coordinate system was not necessary and the problems associated with scale maintenance were elimated, since the computer algorithm makes the necessary scale and registration adjustments for each photograph. For instance, the first step is to input the aircraft's altitude, the elevation of the terrain, enlargement size, and the photo system's field of view. Then, several reference points (the corners of the photograph) were digitized by touching the tablet stylus to those several points in a pre-determined order to establish the X-Y coordinate system. The computer then calculated scale and registration factors for the frame based on the enlargement size, altitude, field elevation and field of view. The operator could then digitize the points of an existing landmark with a known lat/lon, usually a runway centerline or a VOR Station. Finally knowing the orientation of the photograph (runway heading) the lat/lon of the center of the photograph could be computed. In all cases the camera was leveled before each set of frames was taken. Based on this fact, the center of the photograph is assumed to be the exact location of the aircraft, ±100 feet.

Each photograph was time tagged so that the position data obtained could be correlated to the TDL-711's indicated position. Using the lat/lon of the actual aircraft position and the Loran indicated lat/lon position, northing, easting, alongtrack and crosstrack error components were calculated for each photograph.

4.3 LORAN-C ACCURACY

Through the use of the aircraft's true position, and the navigation and Loran-C data recorded from the Loran-C navigator, many accuracy parameters could be determined. These include:

- easting and northing position errors
- Loran-C time difference errors
- total system alongtrack and crosstrack errors
- navigation sensor alongtrack and crosstrack errors
- navigation computer alongtrack and crosstrack errors
- flight technical error

A diagram defining these error relationships is shown in Figure 4.2. The navigator RDU data stream provides Loran-C derived latitude and longitude, crosstrack deviation (flight technical error -- FTE) and distance to waypoint (DTW) data. From these parameters, and the waypoints which define the approach course, the other error components are calculated:

Given:

$\left.\begin{array}{l} LAT_D \\ LON_D \end{array}\right\}$ latitude/longitude derived from the DME data

$\left.\begin{array}{l} LAT_L \\ LON_L \end{array}\right\}$ latitude/longitude derived by the Loran-C navigator

$\left.\begin{array}{l} \text{FTE - Loran-C flight technical error} \\ \text{DTW - Loran-C distance to waypoint} \end{array}\right\}$ recorded data

$\left.\begin{array}{l} LAT_{TO}, LON_{TO} \\ LAT_{FR}, LON_{FR} \end{array}\right\}$ coordinates of the "to" and "from" waypoints

Find:

$\left.\begin{array}{l} \Delta N \\ \Delta E \end{array}\right\}$ Loran-C navigation error in northing and easting coordinates

TSCT - Total system crosstrack error (aircraft position relative to intended course)

ATD - Alongtrack distance

$\left.\begin{array}{l} NSAT \\ NSCT \end{array}\right\}$ Loran-C navigation sensor error in along and crosstrack coordinates

Step 1: Find northing and easting errors

$$\Delta N = LAT_L - LAT_D$$

$$\Delta E = (LON_L - LON_D) \text{ Cos } (LAT_D)$$

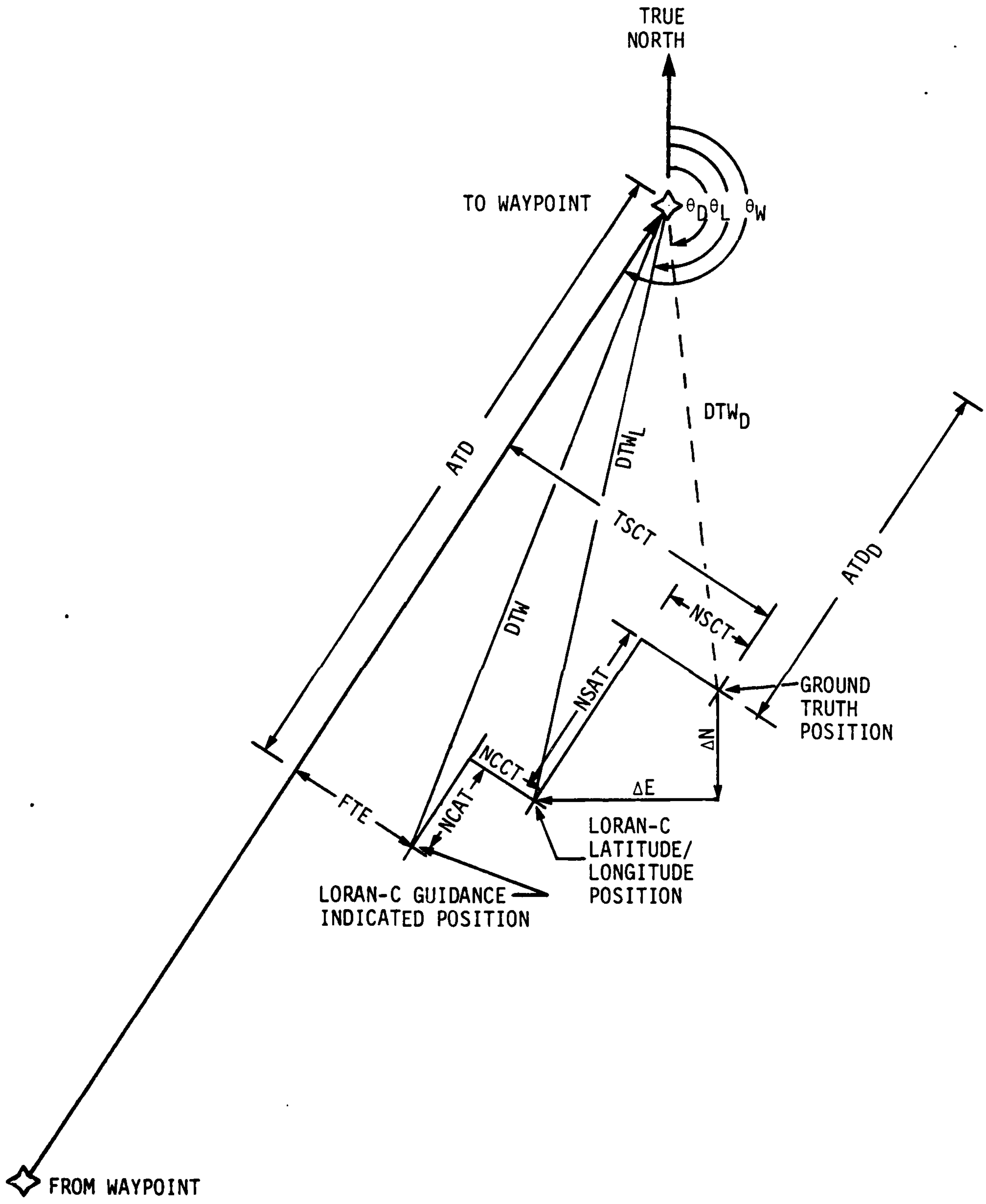

Figure 4.2 Loran-C System Error Geometry

Step 2: Define Course Geometry

The angle θ_W is the reciprocal angle of the desired course between the "from" waypoint and the "to" waypoint. This angle is calculated using the great circle bearing equation in Appendix A with the "to" waypoint and "from" waypoint coordinates used as input data.

Step 3: Find True Aircraft Position

The angle θ_D is the reciprocal angle of the aircraft's bearing to the "to" waypoint as measured from the aircraft's true position. The true distance to waypoint, DTW_D, and the angle θ_D are calculated using great circle distance and bearing equations in Appendix A with the "to" waypoint coordinates used as input data. Then TSCT and ATD are determined as follows:

$$TSCT = DTW_D \cdot \sin(\theta_W - \theta_D)$$
$$ATD_D = DTW_D \cdot \cos(\theta_W - \theta_D)$$

Step 4: Find track-related Loran-C position

FTE and DTW are given

$$ATD^2 = DTW^2 - FTE^2$$

Step 5: Find navigation computer errors

The values θ_L and DTW_L are computed using the "to" waypoint coordinates and the navigator's latitude, longitude coordinates in the great circle distance and bearing equations in Appendix A. The navigation computer errors are then defined using the following equations:

$$NCAT = ATD - DTW_L * \cos(\theta_W - \theta_L)$$
$$NCCT = DTW_L * \sin(\theta_W - \theta_L) - FTE$$

Step 6: Find navigation sensor errors

The navigation sensor errors are found by substracting computer error and flight technical error (in the crosstrack case) from the total system error.

4.4 TIME DIFFERENCE ACCURACY

Time difference (TD) errors were computed at each point where valid Loran-C and DME position data were available. The procedure involves reversing the coordinate conversion process performed by the TDL-711 navigator. Using the true aircraft position from the DME system, distance to Loran-C station values are computed for a spheroidal earth model. The procedure for this computation was taken from FAA Advisory Circular 90-45A, Appendix J. However, earth radii used in the procedure are taken from Reference 3, which uses the World Geodetic System - 1972 Datum. These values are:

equatorial radius (a)	=	6,378,135.00 meters
polar radius (b)	=	6,356,750.500 meters
flattening (f)	=	(a-b)/a = 1/298.26

Once the distance to the station is determined, the propagation time delay for the distance traveled is computed. The primary factor delay is found by dividing the distance traveled by the speed of light at the earth's surface for a standard atmosphere. The speed of light values were taken from Reference 3 by dividing the speed of light in free space (299.792458 meters/μ sec) by the surface index of refraction for the standard atmosphere (1.000338). The speed of propagation at the surface of the earth is 299.6911624 meters/μ second.

Time difference errors were evaluated by computing time difference values from the true aircraft position and substracting the recorded time difference value obtained from the TDL-711 data output. The TD errors determined in this manner represent the difference between TDs that would provide zero position error and those TDs actually recorded. As such, they represent either the inability of the receiver to properly measure TDs from the available signal-in-space (receiver errors), the inability of the navigator to appropriately model the propagation characteristics of the Loran-C signal (modeling error), the inability of the coordinate conversion procedure to converge on a latitude/longitude solution (computer processing error), or the inability of the ground truth positioning system to accurately determine the aircraft's position (reference system error).

The computer processing procedure was validated by inserting recorded Loran-C coordinates in the model and computing time differences. The time differences obtained agreed with those recorded during the test to better than .03 microseconds which was considered to be excellent agreement. The remaining sources of TD errors (receiver error, modeling error and reference system error) are discussed in detail in Section 6.

4.5 STATISTICAL DATA PROCESSING

The error components are evaluated statistically by computing their mean values and standard deviations according to standard formulas:

mean value of N samples $x_1, x_2, \ldots x_n$

$$\overline{X} = \frac{1}{N} \Sigma x_i$$

standard deviation of those samples

$$\sigma_x = \sqrt{\frac{\Sigma x_i^2 - N\overline{X}^2}{N - 1}}$$

4.6 LORAN-C MONITOR DATA

The United States Coast Guard supplied monitor data for the period of time that the tests were being performed (Sept. 1 to Sept. 18, 1982). The monitor data were recorded at monitor receiver site near Kodiak, Alaska. The data consists of twenty-four plots of time difference error at a scale of ±80 nanoseconds full scale. The station records data from all stations of the North Pacific chain and the Gulf of Alaska chain.

In addition to time difference error data, the Coast Guard supplied off-air or unusable times for the Gulf of Alaska chain and the North Pacific chain. These times are recorded for each occurence of a station outage or out of tolerance condition which last for greater than one minute. Outage and out of tolerance times lasting less than one minute are called "momentaries" and are not counted as station unavailable times.

5.0 OPERATIONAL ANALYSIS

5.1 GENERAL

As found in this test and previous Loran-C tests with the TDL-711, the system has been designed reasonably well from the pilot's point of view. In contemporary parlance, it is "user friendly". Most of the features or modes were, at one time or another, used by each of the subject pilots. Some pilots preferred to keep the digital display readout in the XTE mode in order to fine tune their steering performance, since this readout is to .01 nm. Other pilots primarily used the distance to waypoint mode in order to maintain cognizance of their alongtrack position, and used the CDI needle for crosstrack steering. In an event, in the majority of situations the Loran-C signal stability was good enough that pilot FTE, or steering error, was quite low. Even when flying the CDI, needle movement was only affected by aircraft heading or wind, and did not exhibit the significant variations often encountered with either flying VOR radials, or, to a lesser extent, when flying VOR/DME RNAV. It is to be expected that the FTE element in a Loran-C RNAV system use error budget will be substantially lower than the values currently used for the enroute and terminal phases of VOR/DME RNAV system certifications.

For the purpose of explaining the following operational situations the system is considered to be "locked-on" to the Loran-C signal if the decimal point warning lights on the Loran-C control/display unit are extinguished. This is the normal indication that the system is producing valid present position information. When the system was locked-on and the flag indicator on the course deviation indicator was out of view, the system was considered to be producing valid navigation information in terms of course deviation and distance to waypoint. If the system had been locked-on and the decimal point warning lights appeared on the control display unit, the system was considered to have lost one or more of the Loran-C signals. The term "lose-lock" is used to describe this situation.

Four operationally significant circumstances were observed during the conduct of these tests. The first is of minimal importance, and has been observed and documented in a previous test (Reference 4). When initiating a leg change (i.e., changing from a waypoint 1-2 leg to a waypoint 2-3 leg), a period of several seconds is required, during which time the CDI needle is centered and the flag is in view. In an enroute environment, where course changes between legs are usually moderate, this denial of steering information is not critical. However, if this situation occurred in a terminal area situation where course changes of up to 90° can be expected, this system characteristic could possibly result in undesirable airspace utilization under conditions where airspace is at a premium. The principal cause of this problem is the saturation of the computer currently used in the TDL-711. Use of a faster computer or more optimized sofware design should reduce this "dead" time to a more desirable level.

The second problem is of a potentially more serious nature, and has also been observed previously. On several occasions, such as flying east from McGrath to Anchorage, the Loran-C accuracy markedly degraded, with no overt indication to the pilot that such a situation exists. In some cases the Loran-C accuracy diverged from a value of approximately 1 nm to value approaching 20 nm. From the pilot's point of view the system is performing perfectly (i.e., the system is locked-on with an adequate set of signal strengths, the CDI flag is pulled out of view, and CDI steering signals are available). However, without some supplemental position fixing aid such as VOR and DME, or visual fixes, the pilot is not aware that his guidance could be in error by 20 nmi.

The cause of these errors has been traced to difficulties associated with tracking the correct Loran-C cycle in the receiver front end. This problem is discussed in Section 6.3.2. Operational procedures to identify this problem and to eliminate or reduce the possibility of it occurring should be investigated.

The third problem has also been observed and documented in a previous test (Reference 4). The TDL-711 system offers a diagnostic mode which can be utilized to display certain internal navigator data such as signal to noise ratios (SNR's) and other important signal data. This mode is entered by moving the selector to the LEG CHG position and then through series of keystrokes initiated by the pilot. On several occasions when the pilot tried to exit the diagnostic mode, the system displays would become frozen. To resume normal navigation the system had to be reinitialized in flight.

The fourth type of problem occurred on two occasions. For reasons unknown, when a leg change (LEG CHG) was initiated, the CDI needle moved full left then right repeatedly. Again the displays were frozen and the system required reinitialization before navigation could be resumed. Both problems are likely related to software in the navigator.

Finally, no noticeable problems were experienced due to precipitation static. Several of the flights were flown in rain, ice and snow for extended periods of time and not once was there experienced a system problem that could be related to precipitation static. Even at times when the rainfall rates were heavy, no noticeable problems were experienced due to precipitation. The extent to which this performance is due to the static wicks installed upon the aircraft is unknown as the aircraft was not instrumented to measure discharge currents.

5.2 OPERATIONAL RESULTS - TRANSITION SEGMENTS

During the enroute transition phase of testing, no "mid continent gap" was encountered per se. Although at times signals were weak and coverage was poor, the navigator continued to operate and provide good guidance for most of the flight. There were times when the system lost the signal for brief periods of time enroute but these occurances were limited.

On approaches into both Montgomery, Alabama and Little Rock, Arkansas the system lost the signal on the transition and return flights from Anchorage. This problem could be due possibly to some local industrial noise in the area. Further approach testing in these areas might reveal some additional information. Although some bias errors were experienced, the approaches to all of the other airports were accomplished without a loss of signal.

5.3 OPERATIONAL RESULTS-ALASKA

The main purpose of the Loran-C flight test in Alaska was to determine in which areas the system could meet the AC90-45A requirements so that a STC can be issued for those particular geographical areas using the TDL-711.

One of the serious problems mentioned earlier occurred virtually every time the system was utilized in the Anchorage, Alaska area. The Loran-C accuracy markedly degraded in the Anchorage area (approximately a 60 nm radius), with no overt indication to the pilot such a situation existed. Only on one occasion at Anchorage did the Loran acquire the signal on the ground. On all of the other flights the Loran did not acquire the signal until well clear of the Anchorage area. This was true for all directions flown during the test in the Anchorage area. In some cases the error value approached 20 nm. Again, this is without any indication to the pilot unless of course VOR/DME or some other means is used to establish actual position.

In the southwestern area of the state, especially around Bethel, the system performed very accurately. On the Bethel Spur Route the Loran-C navigator guided the pilots to the exact location of the airports. Navigation during this flight was steady and at no time did the system lose-lock. Since there are few other means of navigation in this area, local air taxi operators could benefit greatly by having Loran-C in their aircraft. The Bethel area offers good geometry from the master at St. Paul Island and the secondaries at Port Clarence and Narrow Cape. In addition this area is right in the heart of good Loran-C coverage where good strong signals can be reliably received.

In the northern areas around Galena, Ambler and Kotzebue the system experienced large errors but of a lesser magnitude than those observed near Anchorage. Errors in excess of five miles were observed in this area. Navigation was always steady with no loss-of-lock but large bias errors were experienced. This area is outside of the predicted USCG Loran-C coverage, mainly because it is so far from St. Paul Island, the Master station. Further testing should be conducted in this area to determine the repeatability of the errors.

Overall the TDL-711 Loran-C navigation system performed very accurately over the course of the flight test experiment. Although several anomalies were noticed in certain geographical areas, the TDL-711 was found to be very accurate when it received good signals and was straightforward to operate. In good coverage areas the system acquired signals within 2.5 minutes. Two generic operational problems

arose during the tests. In areas where the signal levels were expected to be low, the system often times did not acquire signals on the ground or in the air. In addition, the system may acquire an erroneous position with no indication to the operator that it has done so in these areas.

6.0 ERROR ANALYSIS RESULTS

This section contains a discussion of the results and analysis of the processing performed upon the data recorded in Alaska. The analysis is divided into six sections which include:

- chain operation
- DME system performance
- receiver performance
- pilot performance
- photo data analysis
- overall performance

6.1 CHAIN PERFORMANCE

During the Alaska flights the North Pacific chain was utilized almost exclusively. On a few occasions in the Anchorage area when the receiver would not lock onto the North Pacific chain, attempts were made to acquire the Gulf of Alaska chain. These attempts were equally unsuccessful and so the only useful navigation data were obtained with the North Pacific chain. The triad used for navigation was:

time difference A - Port Clarence/St. Paul Island
time difference B - Narrow Cape/St. Paul Island

A review of the Coast Guard monitor data showed that the time difference errors, as recorded at the Kodiak monitor site, were usually less than ±40 nanoseconds. On some occasion however, particularly on flights 9-04, 9-06 and 9-07, the TDA error at Kodiak (Yankee Station) was as large as -80 nanoseconds. This error value however, is on the order of the minimum time difference resolution of the TDL-711 and is not considered significant in affecting Loran-C operational accuracy.

It should be noted that while the Kodiak station monitors the Port Clarence signal it does not control that station's phase adjustments.

Five instances of unusable time were recorded for the master station at St. Paul Island during the period of time from 9-01-82 to 9-18-82. None of these times coincided with the times that the test flights were in progress. The unusable times totaled 23 minutes for the 19 days producing a system availability rate of 99.92% during the test period. The availability was 100% during the tests.

The ability of a receiver to identify and track the correct cycle of the Loran-C signal depends, to a large extent, upon a parameter called envelope-to-cycle difference (ECD). ECD is the time relationship between the phase of the 100 KHz carrier signal and the time origin of the pulse envelope waveform[5]. Ideally, ECD is zero when the 30μ second point in the pulse envelope corresponds precisely to the third cycle zero crossing of the carrier signal.

In October of 1982, subsequent to the test period, the U.S. Coast Guard modified the ECD control value for the master station at St. Paul

Island. The monitor receiver is now located at Spruce Cape near Kodiak. Prior to October of 1982 the master ECD control value at Spruce Cape was +1.4μ seconds. The control value was reduced by 1.8μ seconds and is currently -0.4μ seconds. ECD values at locations remote from the monitor will differ from the value measured at the monitor due to differences in surface electrical properties and atmospheric conditions.

Officials at the 17th Coast Guard District in Juneau were contacted and asked to comment upon the difficulties that were encountered during the test in acquiring the Loran-C signals in the Anchorage and Fairbanks areas. Their reply indicated that the reduction in the control ECD value at the monitor should improve the ECD conditions in the Anchorage area. Master ECD values in the remainder of the test area should likewise be equal to, or better than, those at the time of the flight test. The Coast Guard assessment is based upon previous experience and knowledge of the terrain and not upon quantative data taken in the test area.

In summary, the North Pacific chain was operating within the normal time difference accuracy[5] and system availability ranges during the performance of the flight tests. Since the time of the test the Coast Guard has modified the control ECD on the master station. The Coast Guard believes that this change will probably improve ECD values in the flight test area.

6.2 DME SYSTEM PERFORMANCE

In order to obtain a satisfactory position fix, a minimum of two DME stations had to be received. In addition, the aircraft had to be in such a position so as to have a satisfactory crossing angle of the DME lines of position, which is typically any position away from the baseline or baseline extension connecting the DME stations. In several areas, when two or three stations were being received, they were directly ahead or behind the aircraft causing unsatisfactory station geometry conditions.

Problems affecting the DME measurements themselves occurred on a few occasions. Once near Nome, as the aircraft descended to land, a DME transponder located on a ship was being received. The apparent position of the aircraft, as determined by the DME positioning system, was moving north-north east while the heading indicator on the aircraft showed a westerly flight path. In all probability, the signal to and from the ship's transponder was experiencing reflections off the ocean surface due to the low grazing angle of the signal. A similar problem occured at King Salmon on one occasion. As the aircraft descended below 200 ft., the DME remained locked on to a station some 60 miles away. The position as determined from the DME system became very erratic and was rejected for this reason.

When three or more measurements were being used to establish the aircraft position, the root mean square value of the DME residuals usually provided an effective means of identifying and rejecting occasionally erroneous DME measurements. When only two DME stations

are used, the least square estimator drives the residual values to zero, thus rendering the RMS check ineffective. In these instances only the general continuity of the DME measurements could be used to validate the position fix.

Bias errors in the DME measurements, caused by transponder delay errors, can also affect the accuracy of the DME positioning system. These biases can be estimated in instances where multiple stations are being received and the estimates used to improve the position fixing accuracy. Since the DME positioning system was considered to be sufficiently accurate to establish the enroute performance of the Loran-C system, no effort was made in the data reduction process to reduce position errors caused by DME bias errors.

By far the greatest single problem in using the DME positioning system in Alaska is the paucity of DME stations in the test area. DME coverage was quite good in the Anchorage, Fairbanks and Nome areas where four to five stations were usually received. DME coverage was satisfactory in the King Salmon and Bethel areas where two to three stations were received. Coverage was unsatisfactory in the areas around McGrath, Ambler and Kotzebue where zero to two stations were received. Often, when two stations were received, they were both near the same airport, one being an enroute VORTAC, the other being an ILS DME facility.

An overall picture of the availability of the DME positioning system and the performance of the Loran-C system is shown in Figures 6.1 through 6.5. Shown on these diagrams are times when the DME positioning system and the Loran-C system were functioning on the five days of extensive flight testing. It is quite evident that long periods of time occur between DME position fixes in many areas. To check the operation of the Loran-C system in these areas the DME measurements that were available were monitored for continuity and consistency. Generally it was found that the Loran-C system provided consistent performance during these periods in terms of time difference errors unless a system initialization had occurred. When initialization occurred, the system time difference errors could change considerably.

6.3 RECEIVER PERFORMANCE

Receiver performance is divided into four categories for analysis purposes. These categories are:

- receiver availability
- time difference performance
- coordinate conversion performance
- guidance performance

6.3.1 Receiver Availability

In the Anchorage and Fairbanks areas, the availability of Loran-C guidance from the TDL-711 was very poor. This was consistently true on each day that the unit was flown in these areas. This fact is

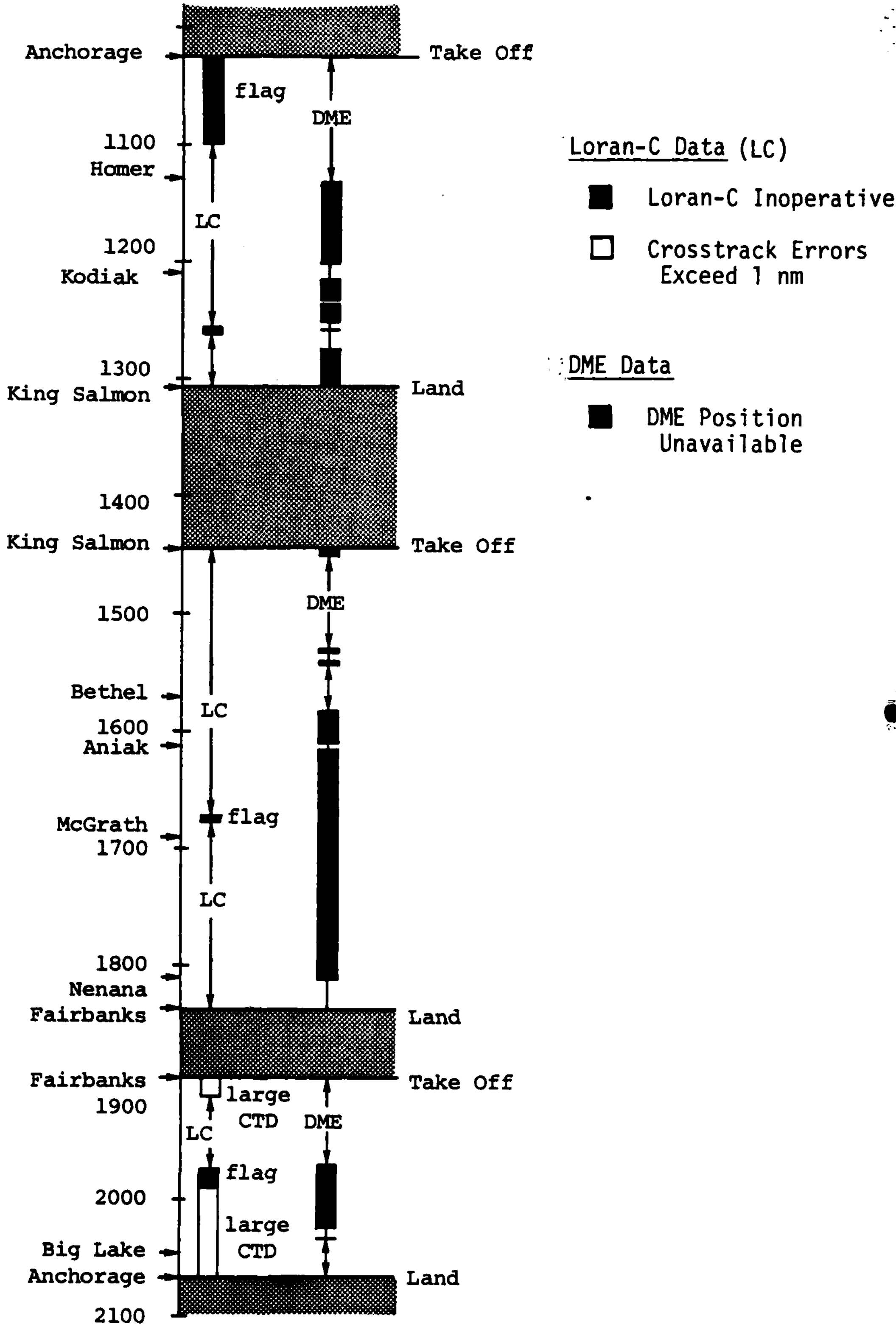

Figure 6.1 Event Diagram
9-04-82

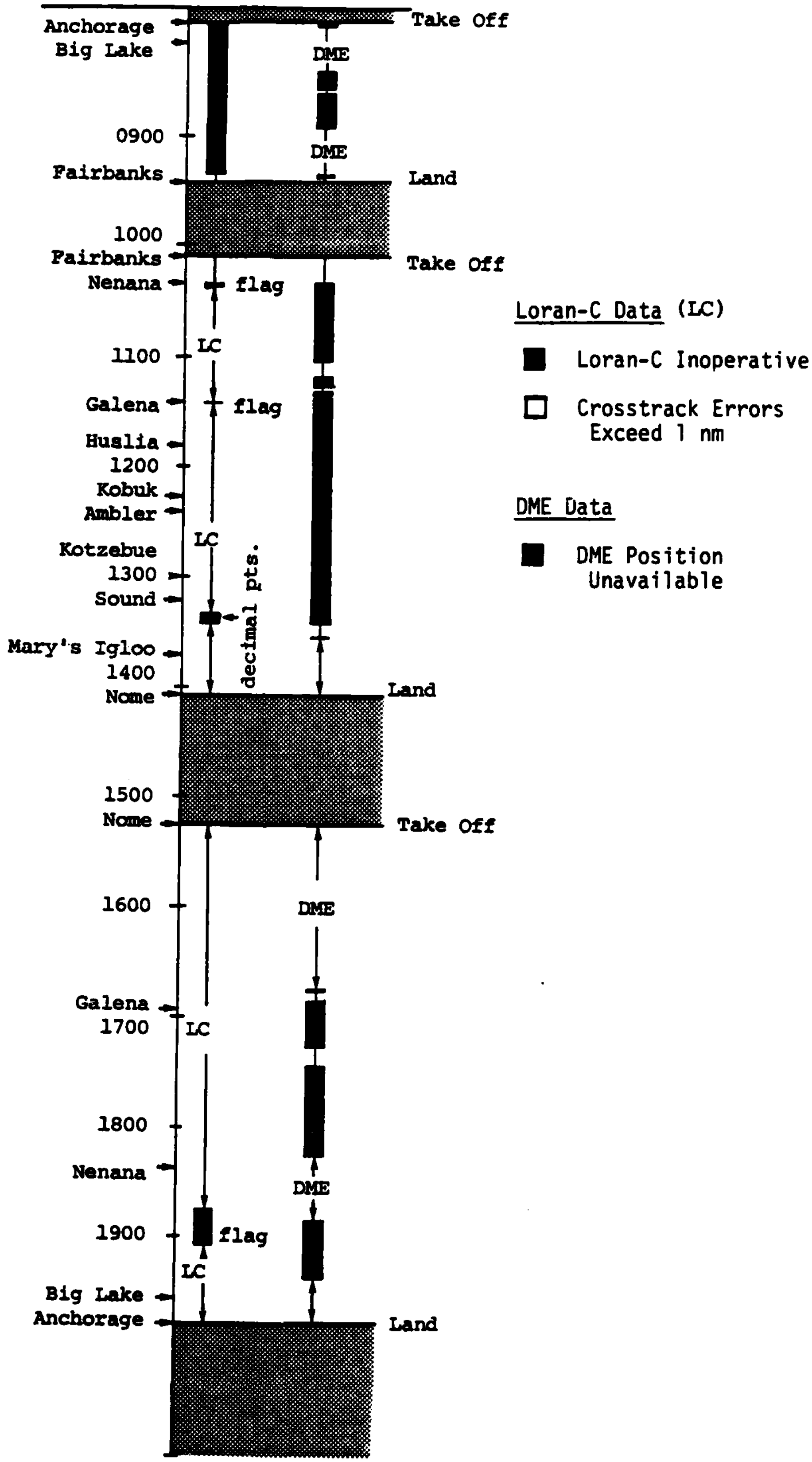

Figure 6.2 Event Diagram 9-06-82

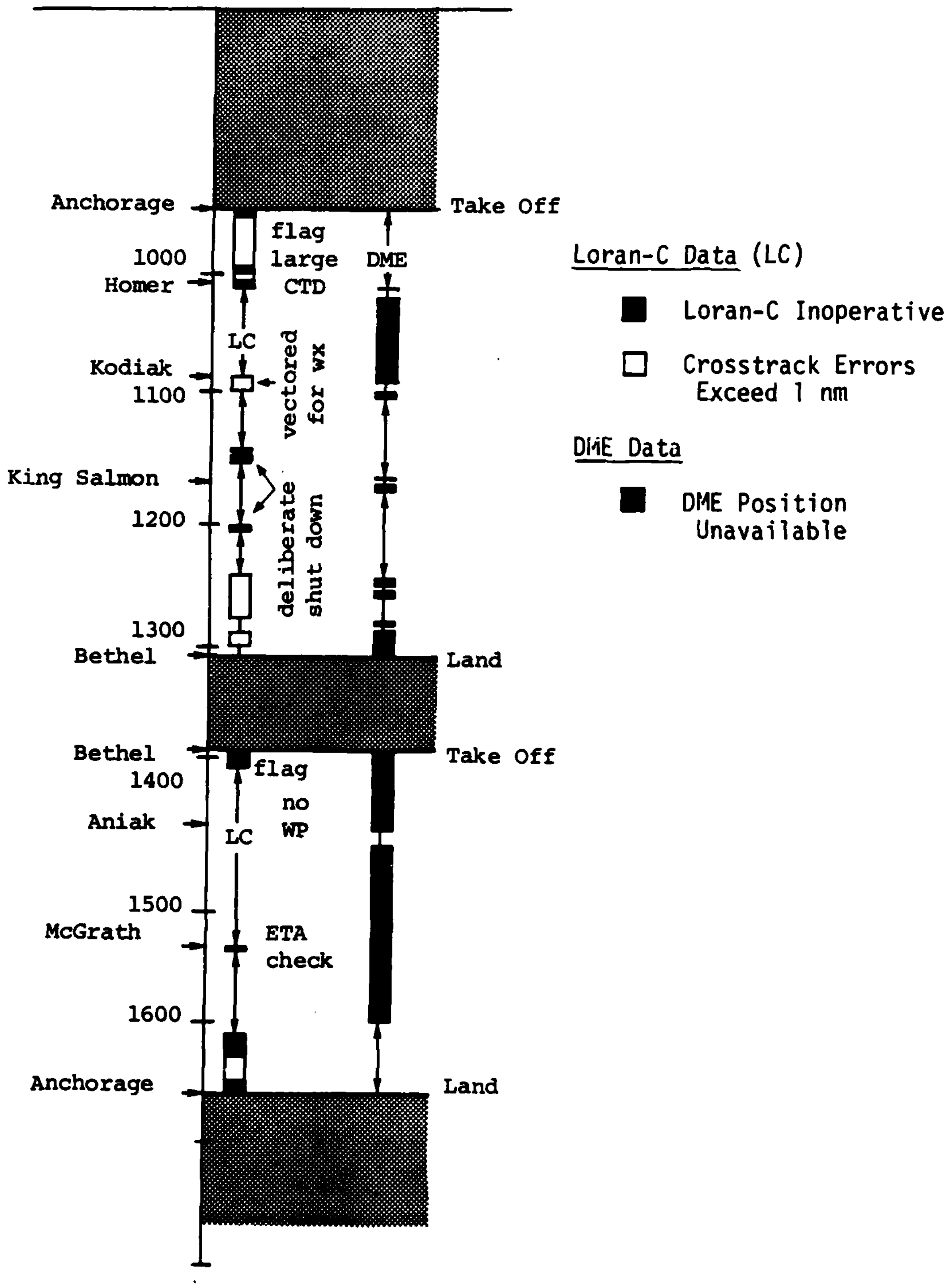

Figure 6.3 Event Diagram 9-07-82

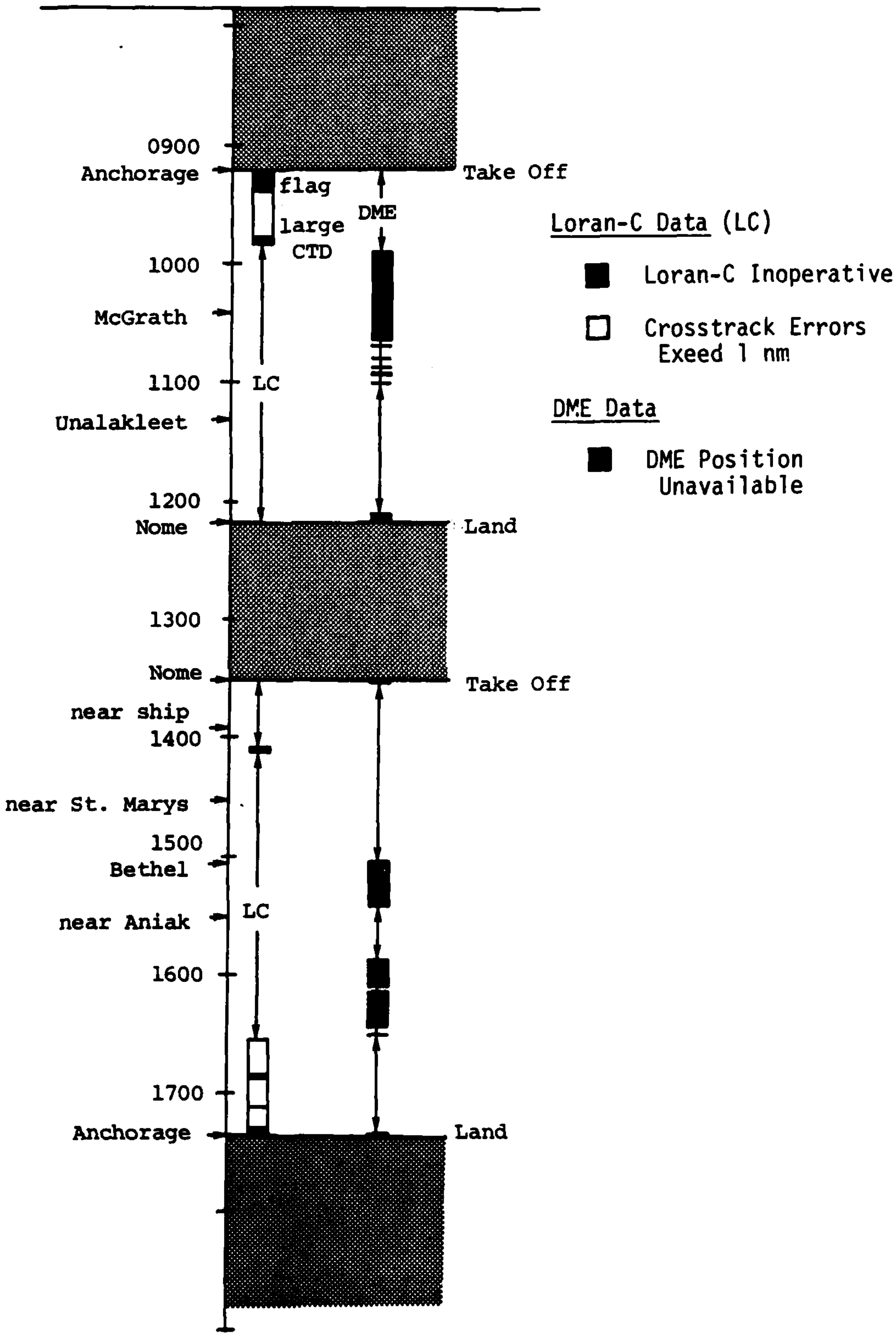

Figure 6.4 Event Diagram 9-09-82

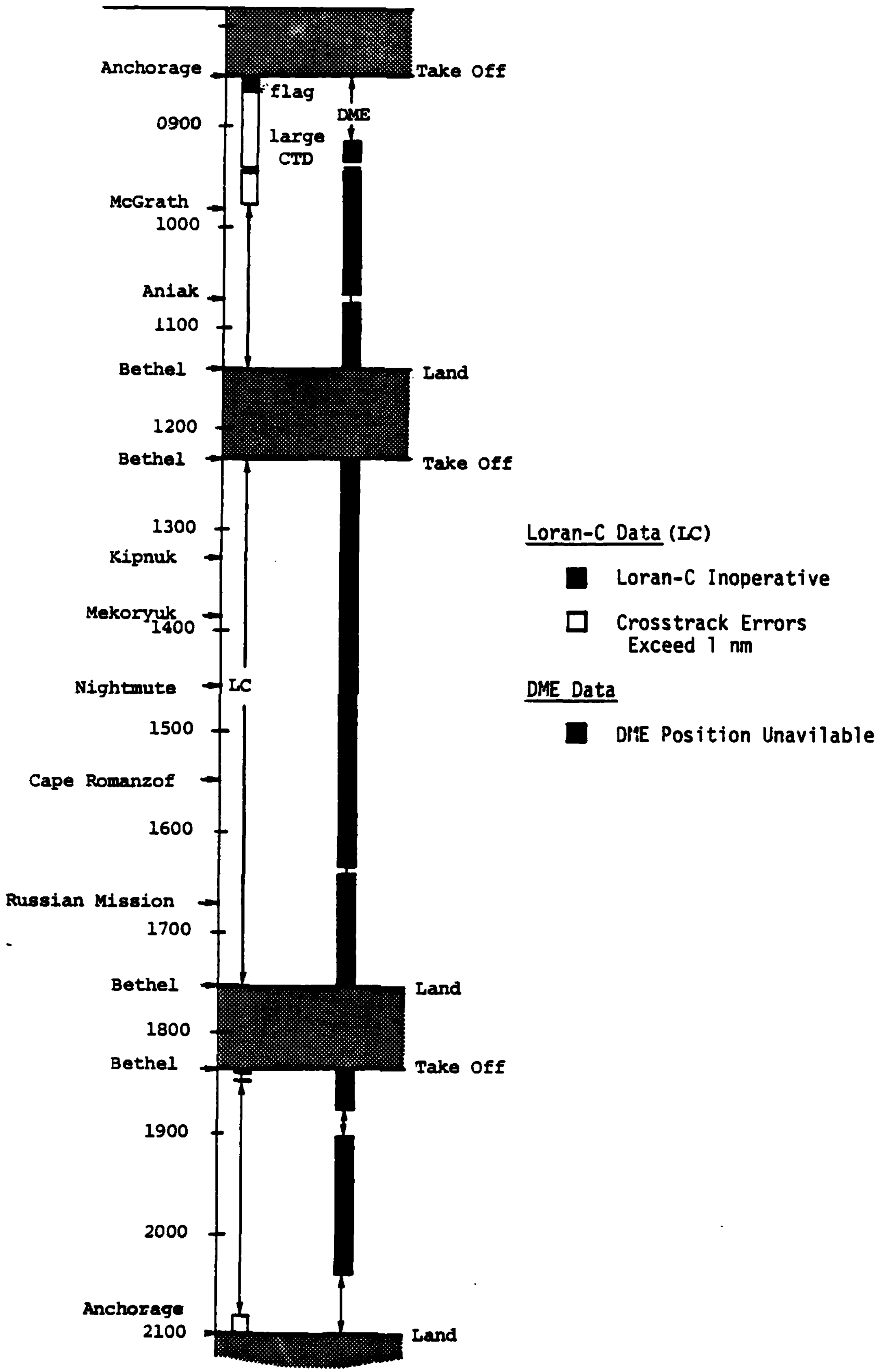

Figure 6.5 Event Diagram 9-10-82

shown in the Loran-C column in Figures 6.1 to 6.5. On flight 9-04 the unit failed to acquire the signals for about one hour until the aircraft was about 100 nm south-south west of Anchorage near Homer. Two brief loss of lock occurences happened outside the Anchorage area, one near King Salmon and one near McGrath. The first of these was operator induced to demonstrate airborne reinitialization. On the return trip from Fairbanks to Anchorage the unit had large errors throughout this flight segment and failed to operate at all of one seven minute period.

This pattern of operation was repeated on flight 9-06. The unit never acquired the signals until the aircraft was about 10 nm south of Fairbanks on the flight segment from Anchorage. Loss of signal again occurred at about 1850 as the aircraft again approached the Fairbanks area.

On flight 9-07, the receiver did acquire the signals shortly outside of Anchorage but the flight crew recognized a large error in the Loran-C position and chose to fly using VOR guidance, thus producing large errors in the guidance information. The system was reinitialized near Homer and the errors, observed previously, diminished. The unit again lost the signals shortly after 1600 as the aircraft entered the Anchorage area. Two deliberate system shut downs occurred on this flight and several track deviations for weather and ATC requests were performed between Kodiak and Bethel. On the flight leaving Bethel, no waypoint was entered in the unit until the aircraft cleared the Bethel area and proceeded on the enroute track. The unit was functioning at this time but was not providing guidance information.

On flight 9-09 the unit functioned very well outside the Anchorage area. This was repeated on flight 9-10. The unit operated without any loss of signal problems throughout the entire five and one half four circuit of the Bethel Spur Route in the area west and north of Bethel.

6.3.2 Time Difference Performance

Time difference errors were determined by applying the data processing procedure outlined in Section 4.4. Evaluation of the time difference error provided information on the receiver's ability to process the Loran-C signal and identify the proper cycle crossing and evaluate the propagation model used by the TDL-711 navigator for position determination.

Figures 6.6 through 6.15 show the time difference errors for the five days of flight testing. Detailed statistical data for these same flights are presented in Table 6.1. These data are taken within a 50 nm radius of the cities and villages shown. As a general rule the following rules apply to interpreting the time difference errors:

- TDA refers to the Port Clarence/St. Paul Island time difference
- TDB refers to the Narrow Cape/ St. Paul Island time difference

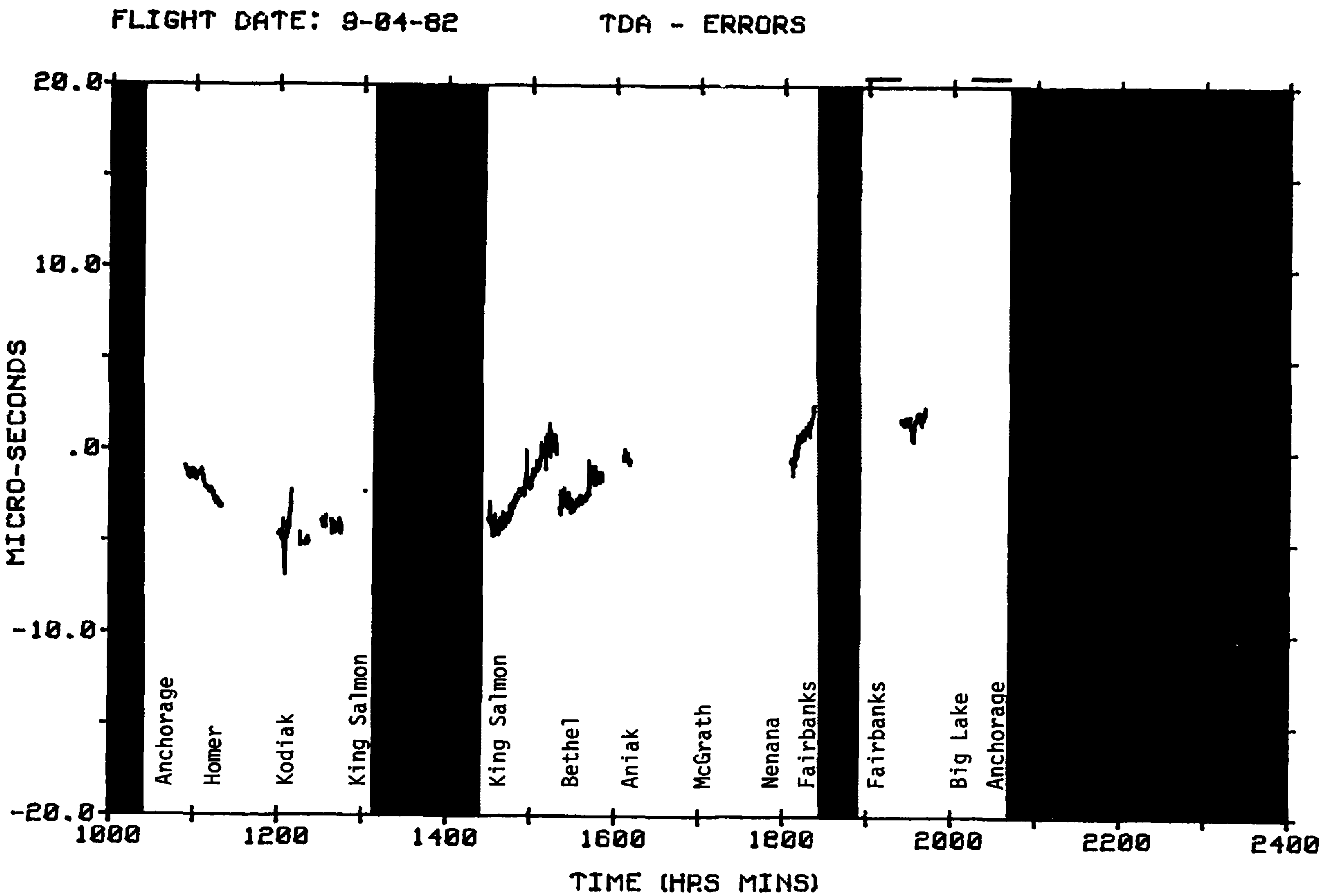

Figure 6.6 TDA Errors, Flight 9-04

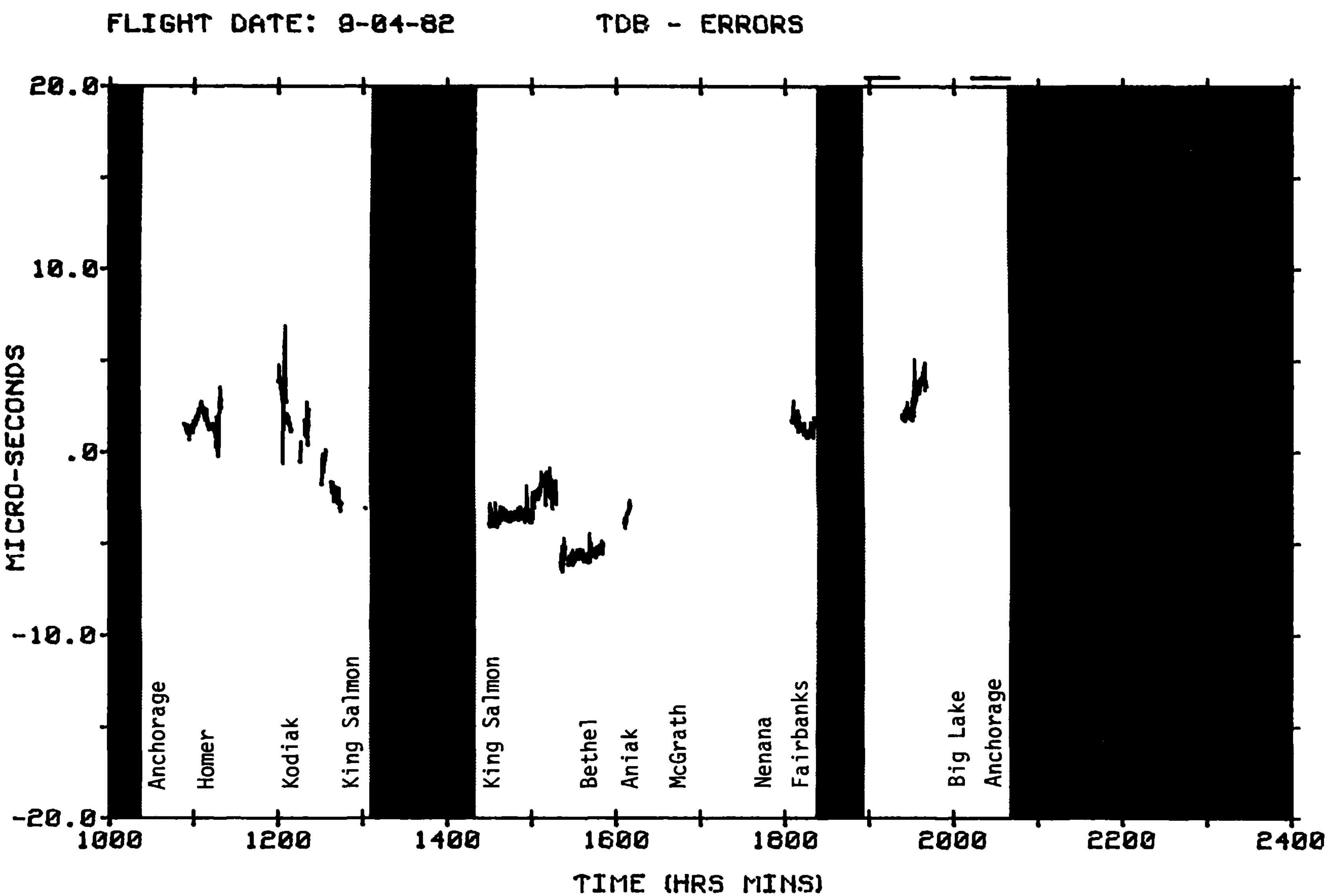

Figure 6.7 TDB Errors, Flight 9-04

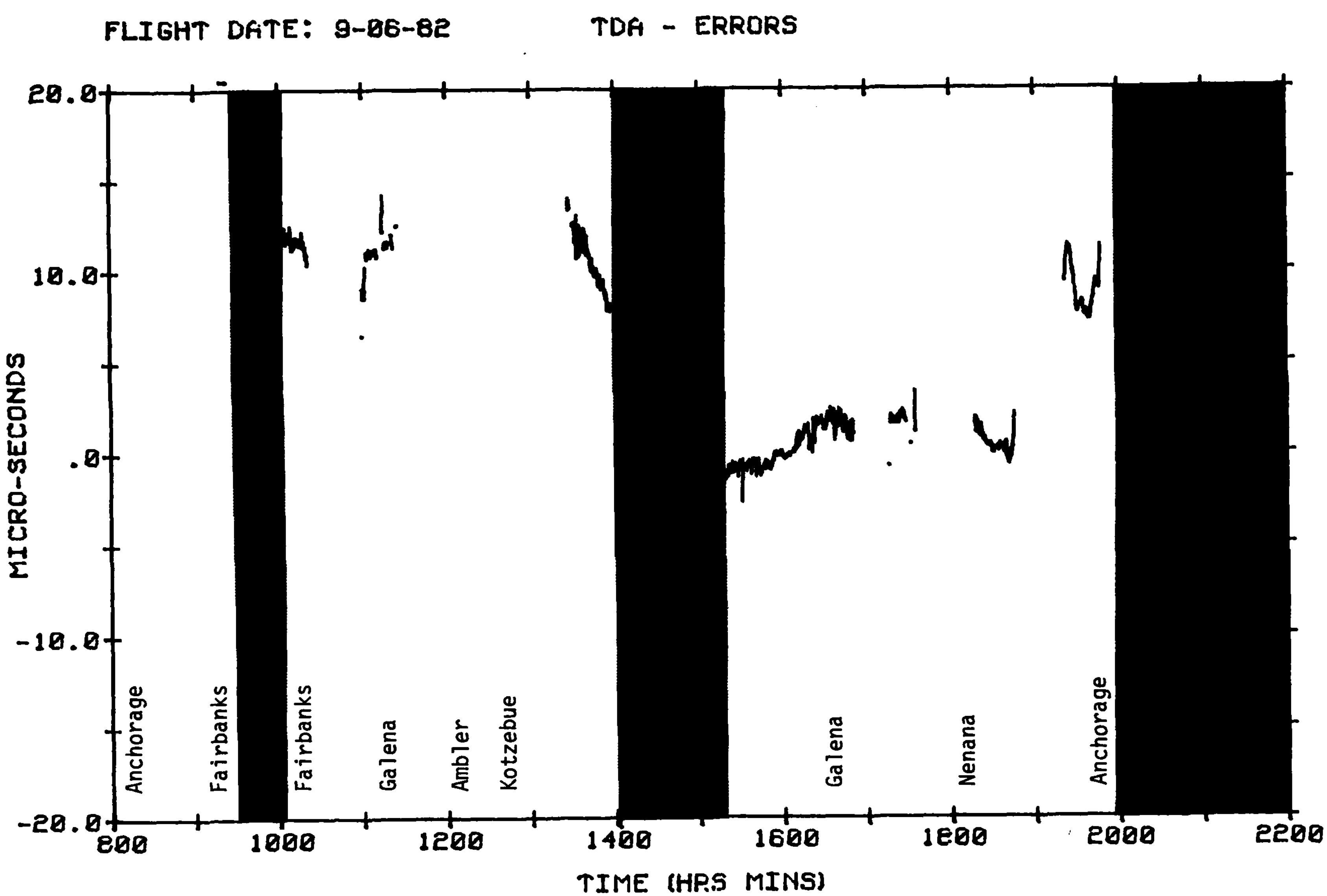

Figure 6.8 TDA Errors, Flight 9-06

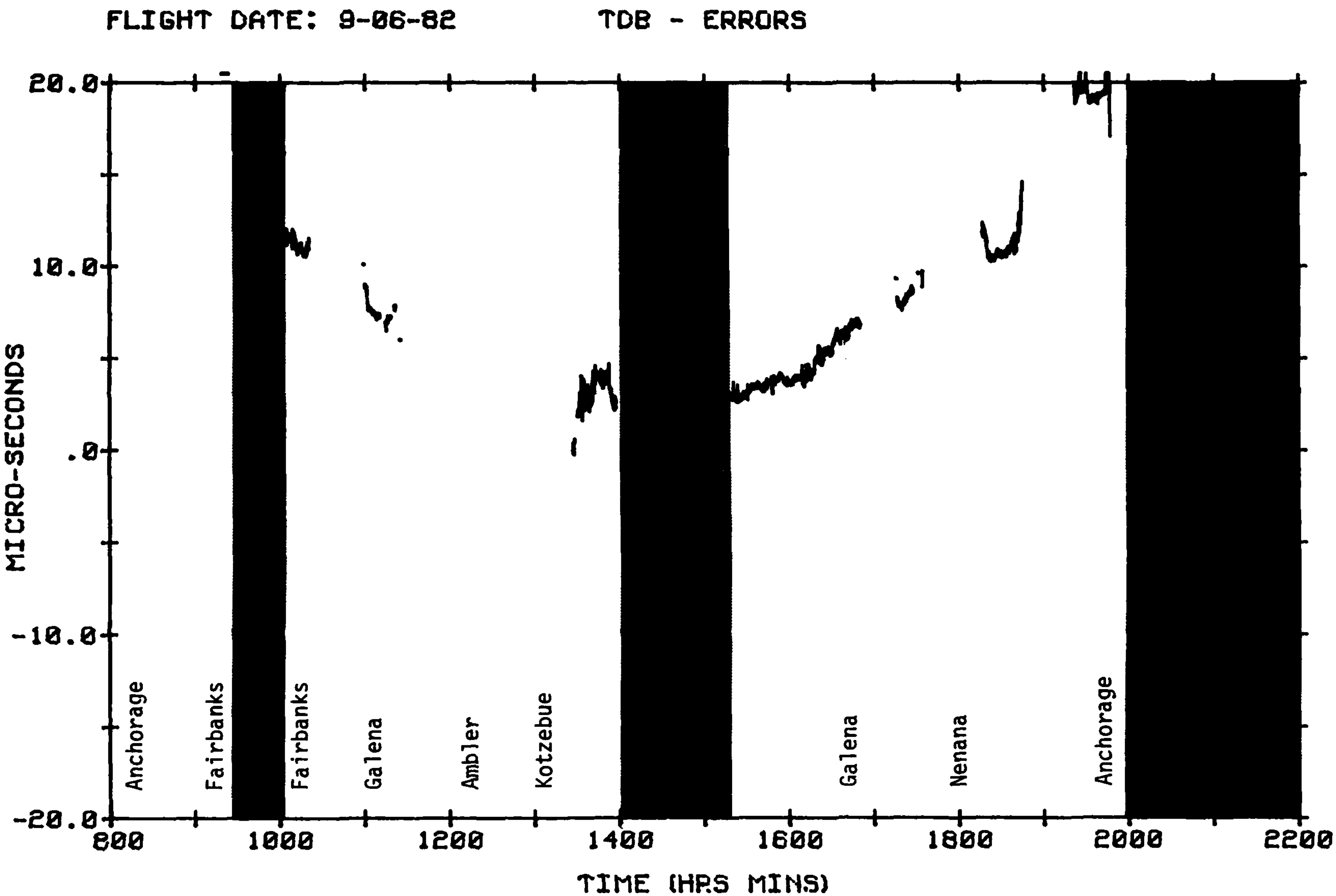

Figure 6.9 TDB Errors, Flight 9-06

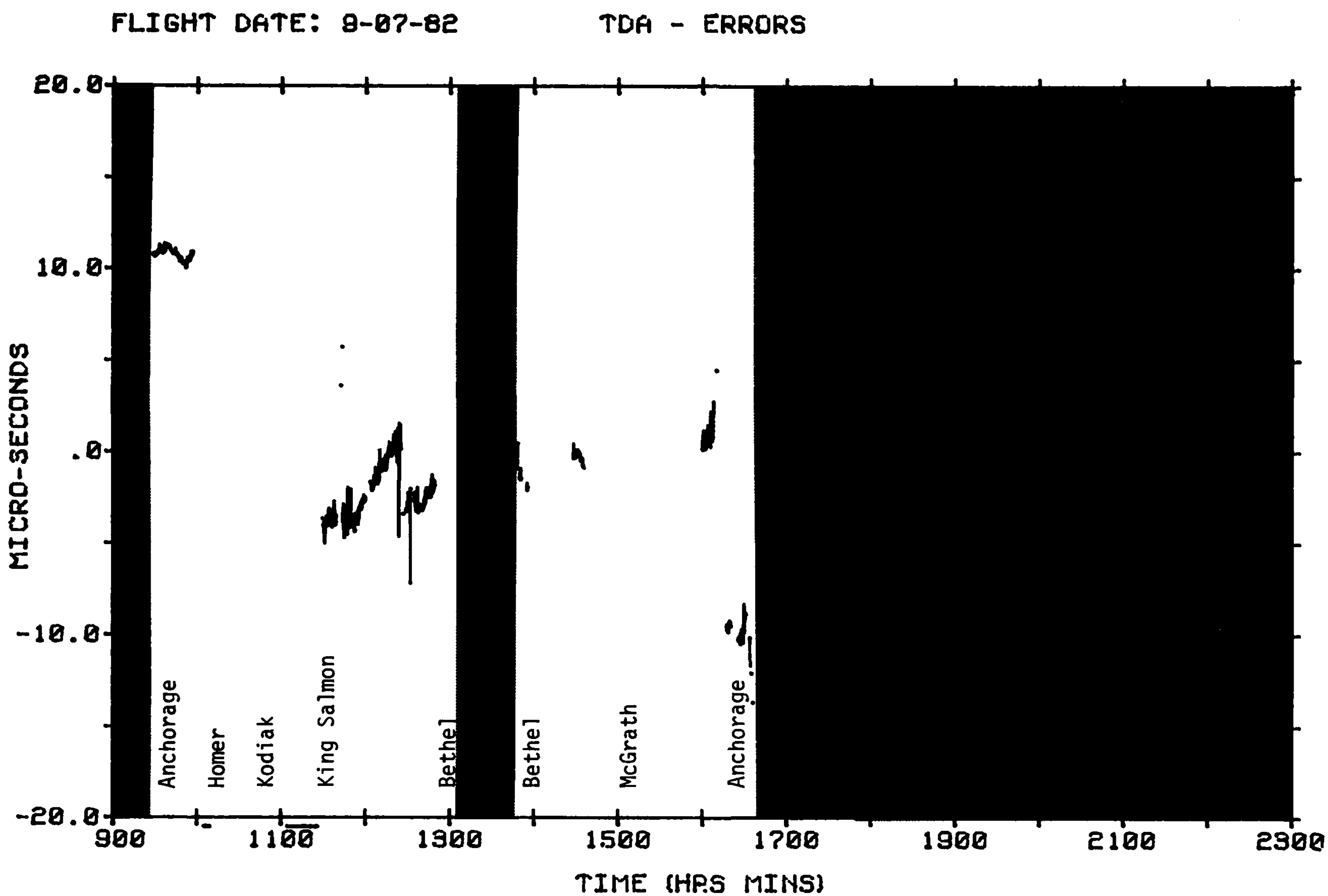

Figure 6.10 TDA Errors, Flight 9-07

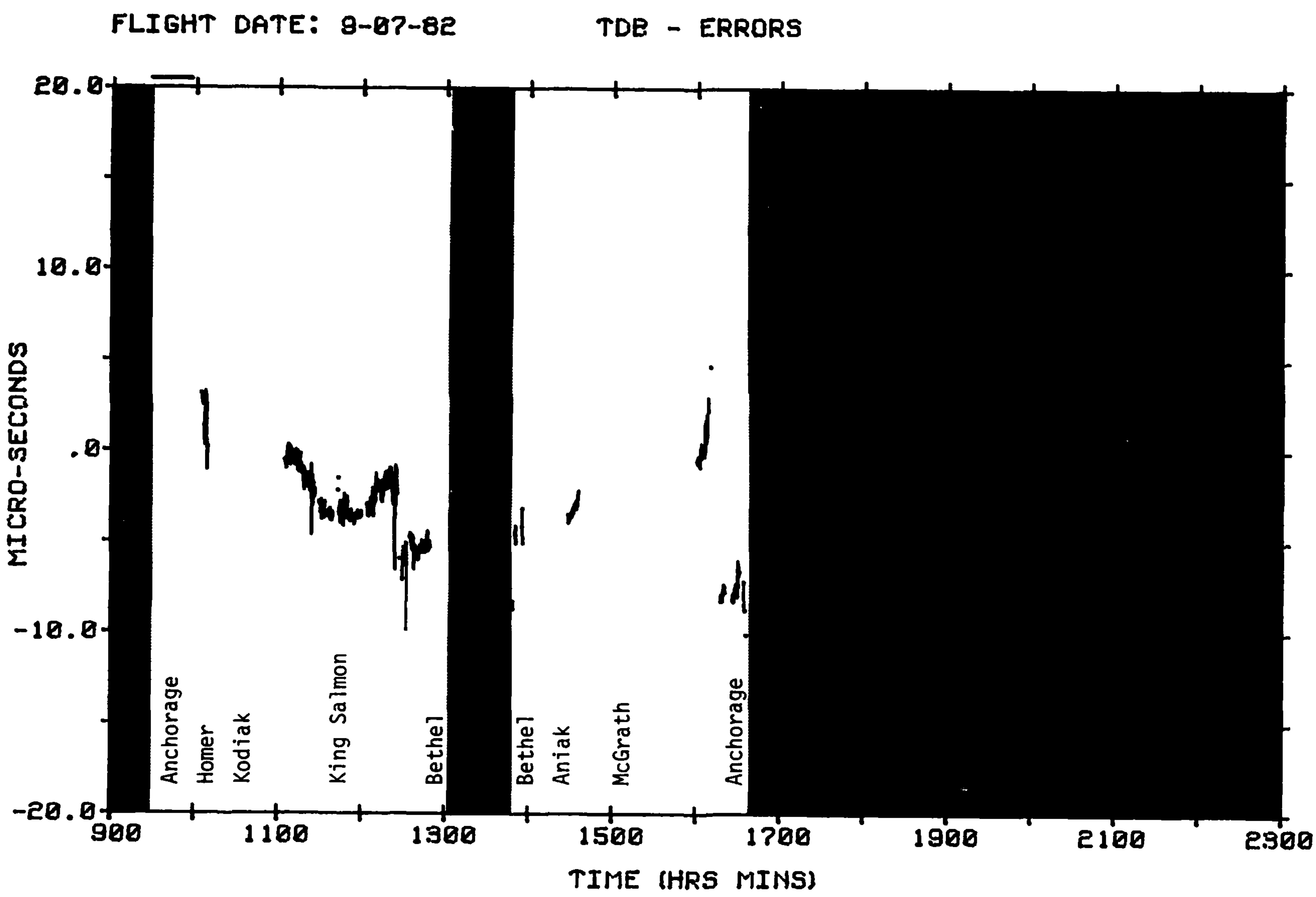

Figure 6.11 TDB Errors, Flight 9-07

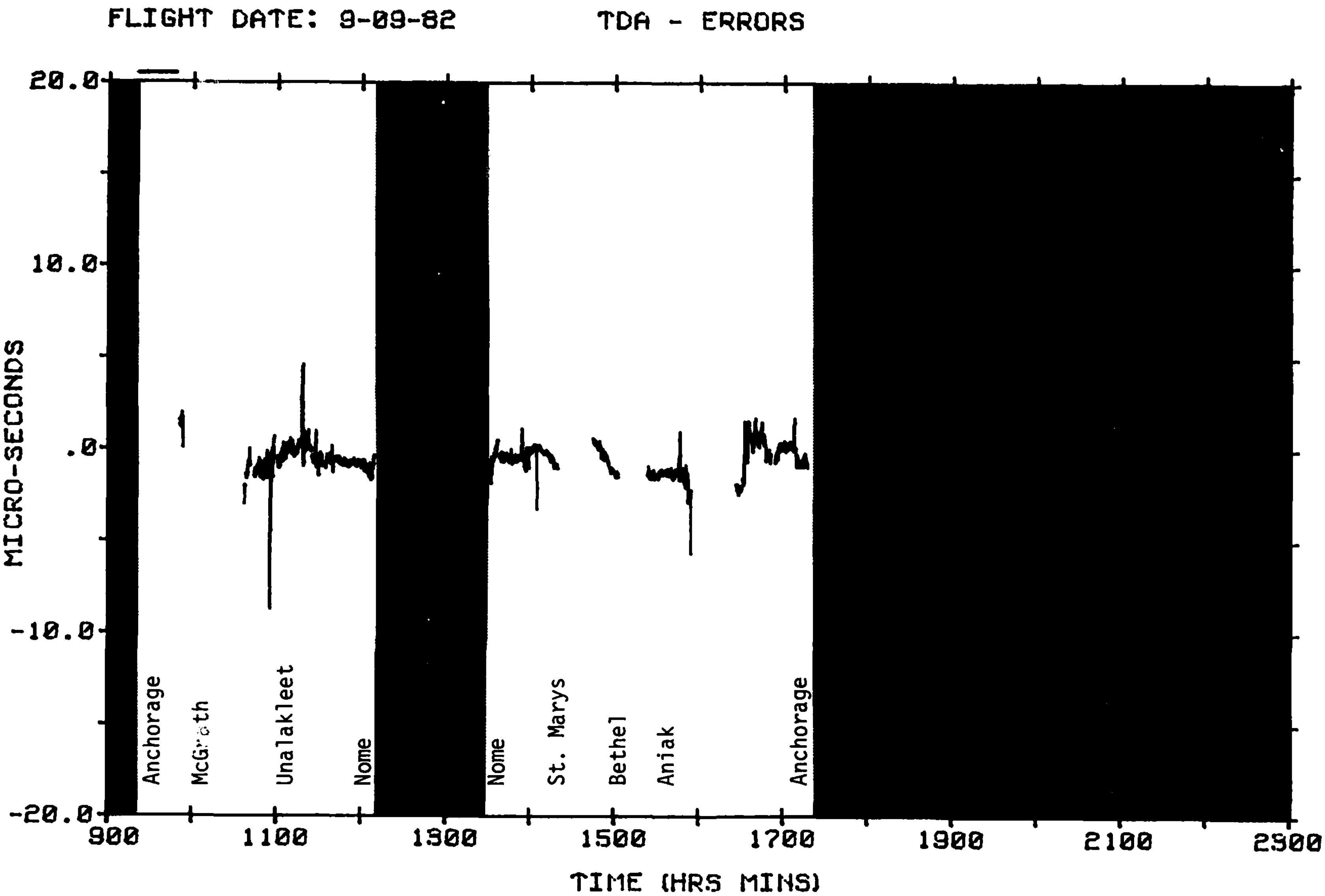

Figure 6.12 TDA Errors, Flight 9-09

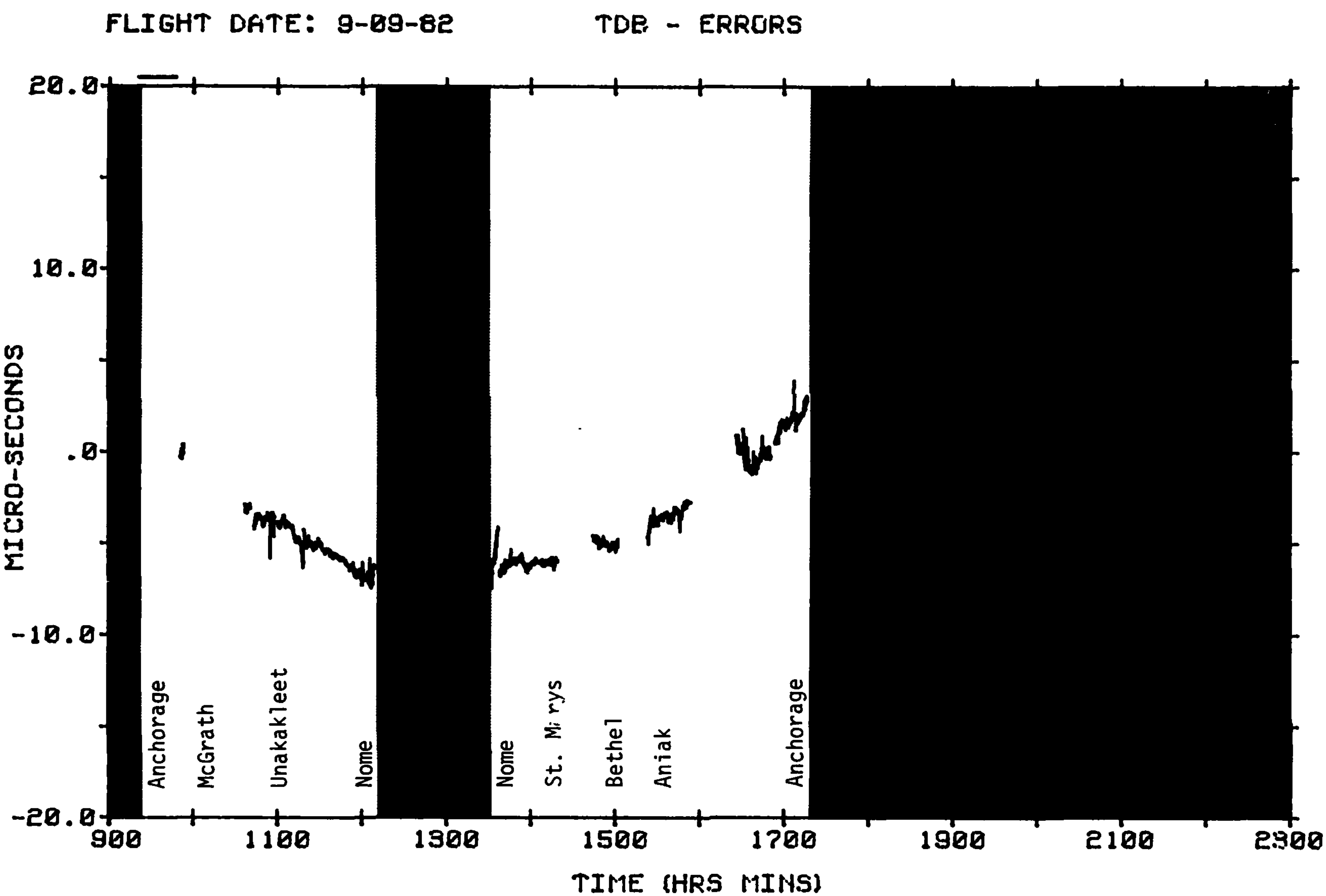

Figure 6.13 TDB Errors, Flight 9-09

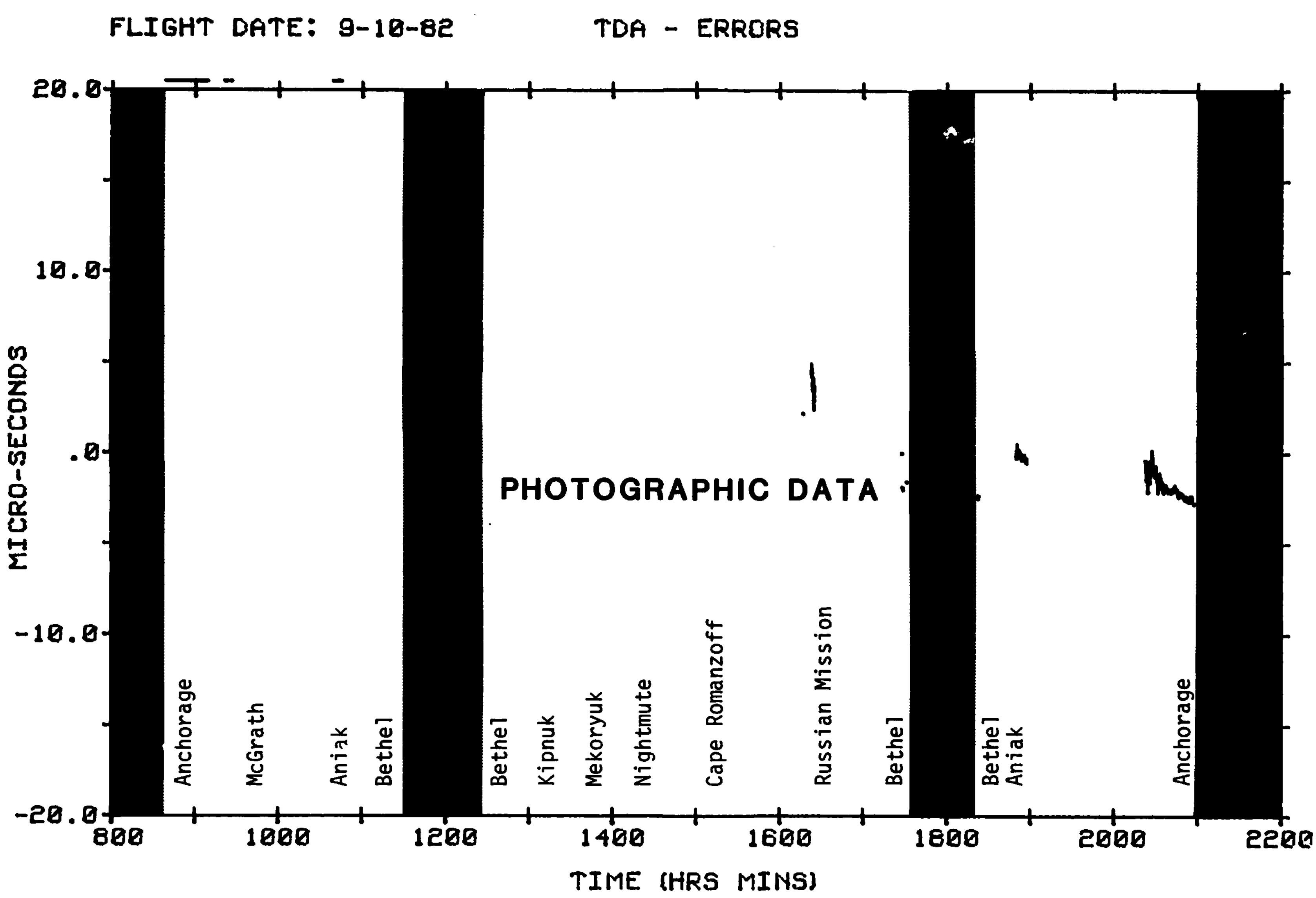

Figure 6.14 TDA Error Flight 9-10

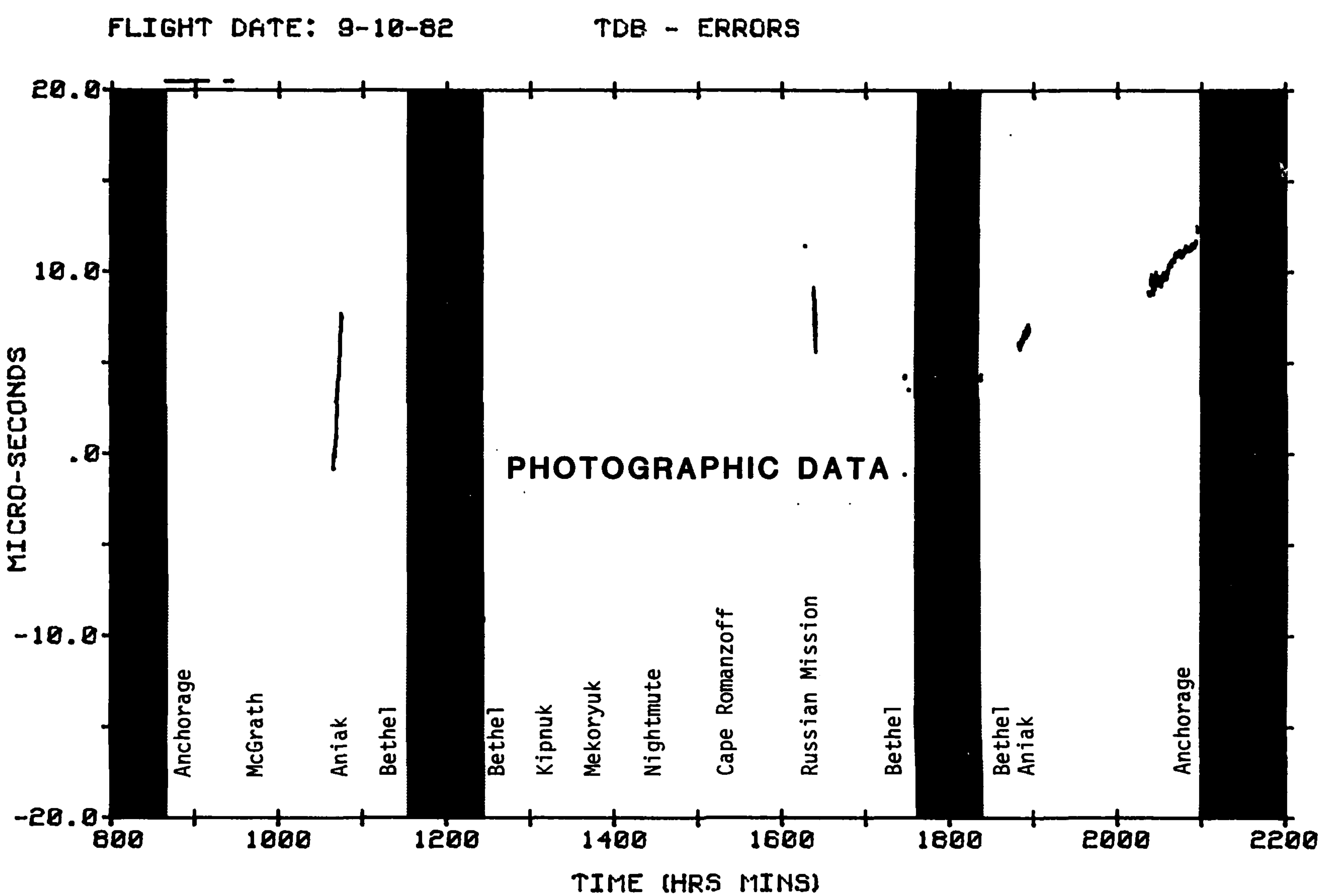

Figure 6.15 TDB Errors, Flight 9-10

Table 6.1 Mean Time Difference and Position Errors

CITY	DAY	# PTS	TDA(μs)	TDB(μs)	ΔN(nm)	ΔE(nm)
KODIAK	9-04	70	- 4.587	2.429	- .804	- .334
	9-07	90	-26.431	- .085	-4.126	- 2.723
KING SALMON	9-04 in	31	- 4.190	- 2.521	- .583	- .365
	9-04 out	117	- 3.715	- 3.545	- .421	- .374
	9-07	139	- 3.423	- 3.413	- .398	- .360
BETHEL	9-04	134	- 2.211	- 5.563	- .116	- .530
	9-07 in	61	- 2.565	- 5.356	- .149	- .497
	9-07 out	12	- 1.376	- 5.153	- .021	- .499
	9-09	97	- .528	- 5.011	- .056	- .507
	9-10	4	- 2.391	4.216	- .369	.427
ANIAK	9-04	26	- .528	- 3.610	- .007	- .379
	9-07	41	- .219	- 3.228	.020	- .341
	9-09	133	- 1.271	- 3.593	- .086	- .383
	9-10 out	35	75.055	3.261	8.876	1.273
	9-10 in	42	- .126	6.443	- .117	.669
NOME	9-06 in	117	9.961	3.423	1.301	.247
	9-06 out	148	- .830	3.171	.039	.455
	9-09 in	126	- .887	- 6.545	- .289	- .886
	9-09 out	123	- .374	- 5.968	- .131	- .819
GALENA	9-06 out	39	11.410	7.255	2.722	2.088
	9-06 in	97	1.630	6.769	.639	1.174
FAIRBANKS	9-04 in	88	.846	1.384	.284	.615
	9-04 out	140	31.583	31.486	9.771	17.631
	9-06 in/am	21	21.099	20.661	6.889	11.994
	9-06 out/am	90	11.615	11.228	3.700	6.027
	9-06 pm	127	.534	10.921	.370	3.066
ANCHORAGE	9-04 in	105	46.425	39.844	6.665	17.340
	9-06 in	137	8.861	19.452	.842	5.606
	9-07 out	119	10.877	35.313	.117	8.673
	9-07 in	14	- 9.513	- 7.827	-1.330	- 2.719
	9-09 out	88	45.863	47.217	6.230	16.294
	9-09 in	125	- .155	1.788	- .091	.294
	9-10 out	99	32.407	34.241	4.268	11.492
	9-10 in	107	- 2.232	11.073	- .734	1.642

- positive time difference error implies one or more of the following conditions:
    - propagation model error in the master signal
    - cycle slip in the master signal
    - cycle jump in the secondary signal
- negative time difference error implies one or more of the following conditions:
    - propagation model error in the secondary signal
    - cycle slip in the secondary signal
    - cycle jump in the master signal
- A cycle slip is defined as the receiver tracking on the fourth or greater cycle, a cycle jump occurs if the receiver tracks the first or second zero crossing in the Loran-C pulse.
- Normally propagation model errors are in the 2-3 μ second range with errors occasionally reaching 4-5 μ seconds. Cycle slip and cycle jump errors are multiples of 10 μ seconds which is the period of the 100 KHz Loran-C signal.

Time differences for flight 9-04 are shown in Figures 6.6 and 6.7. Errors in both channels are generally between the normal range expected of propagation model errors. Near Kodiak the TDA error approaches -5 microseconds indicating a large error in the Port Clarence signal. This signal is traveling over the mountains north of Kodiak and a large modeling error is quite normal. Similarly, at Bethel the TDB signal approaches -5 to -6 microseconds. The Narrow Cape signal passes over the same mountains causing a similar error in TDB at Bethel. In the Anchorage and Fairbanks area all signals travel over the mountains and a cancellation of modeling errors probably occurs due to the time difference nature of the signal.

Figures 6.8 and 6.9 show TD errors observed on flight 9-06 which was flown throughout the northern region of the test area. Only about 10 minutes were obtained in the Anchorage to Fairbanks segment. In this area both TDA and TDB were very large, about 21 μ seconds, indicating a probable cycle slip in the master signal.

Upon leaving Fairbanks the unit was reinitialized, but as shown, large errors on the order of +10 to +12 μ seconds are apparent. At Nome there is almost precisely a 10 μ seconds jump in the TDA data of Table 6.1 between the incoming flight 9-06 and the outgoing flight (9.961 μ seconds versus -0.830 μ seconds). At the same time the TDB error is essentially constant on the inbound and outbound segments (3.423 μ seconds versus 3.171 μ seconds). This would tend to indicate a cycle jump in the secondary signal of TDB rather than a cycle slip in the master signal which would affect both TDA and TDB. Near Anchorage, on the return segment, a large TD jump occurs after the

aircraft passes Nenana. Since it occurs in both TDA and TDB, the evidence indicates a probable cycle slip in the master signal.

Flight 9-07 was essentially a repeat of flight 9-04 except the destination was Bethel rather than King Salmon. The receiver performance on this flight was essentially consistent with the flight of 9-04 outside of the Anchorage area. The plots of Figures 6.10 and 6.11 showing TDA and TDB errors for 9-07 and the data in Table 6.1 for the two days are very consistent.

The jump in TD errors on both days on both channels between King Salmon and Bethel is probably due to a bias error in one or more DME stations used in the DME positioning system. At the point of the jump the King Salmon DME was dropped from the position processing.

Cycle slips or cycle jumps are apparent in both TDA and TDB as the aircraft exits and enters the Anchorage area. TDA error is about +10.9 μ seconds upon leaving Anchorage and -9.7 μ seconds upon return. TDB error is -35.5 on the outbound segment and -7.8 on the return in the evening.

The TD errors shown in Figures 6.12 and 6.13 for flight 9-09 from Anchorage to Nome to Bethel to Anchorage were the most consistent data obtained during the test. Upon leaving Anchorage, TD errors in both channels exceed 40 μ seconds, however, the system was reinitialized and consistent performance was observed throughout the remainder of the flight.

Errors in TDA are near zero throughout the flight. Errors in TDB smoothly decrease to about -6 μ seconds at Nome and then smoothly increase to near zero as the aircraft returns to Anchorage. The error at Nome is consistent with propagation model error in the Narrow Cape signal as it travels over land and mountains north of Kodiak. The system appears to function well even into the Anchorage area on this flight.

The flight of 9-10 consisted of a direct flight from Anchorage to Bethel, the Bethel Spur segment and return from Bethel to Anchorage. During the Bethel Spur segment photographic data was obtained. The route of flight produced little DME positioning system data outside of the Anchorage area as shown in Figures 6.14 and 6.15.

On this flight the system was initialized in the Anchorage area and allowed to operate without operator intervention from Anchorage to Bethel. The system indicated that it was operating properly, but large errors are shown in both TDA and TDB throughout the segment. Apparently the system, once locked on to a signal, did not attempt to verify if it was locked on to the correct signal. This observation strongly suggests that the system should be checked for proper operation and reinitialized in known, good signal areas.

The limited amount of TD error data obtained on this flight indicates that the error in TDB was about 10 μ seconds greater than

that obtained in previous flights at Bethel and Aniak. This is shown in Table 6.1. At Aniak the error is about +6.4 microseconds instead of -3.2 to -3.6 as measured on flights 9-04, 9-07 and 9-09. At Bethel the error, based on only 4 points, is +4.2 μ seconds instead of the -5.0 to -5.6 μ seconds, which was measured on other days. This difference strongly suggests a receiver cycle jump in the secondary signal from Narrow Cape.

Propagation model errors, where they could be separated from cycle errors, were quite consistent with expected performance. As stated in Section 4.4, the TDL-711 propagation model uses a faster propagation velocity than that predicated by theoretical means[4]. It is especially true in the case of signals which propagate over mountainous terrain of poor conductivity, such as the areas west of Fairbanks, Anchorage and Kodiak, as shown in Figure 6.16. These mountains, some of which are the most rugged in North America, appear to have a significant slowing effect on the propagation velocity of the 100 KHz Loran-C signal.

The apparent cycle slip and cycle jump problems experienced during the test could arise from a number of possible sources. Included among these are:

- ECD problems in the area
- poor signal to noise ratio
- interference from other radio systems
- distortions to the signal

It is quite possible that all four problems exist in the Anchorage area.

Possible ECD problems at the time of the test were discussed in Section 6.1. Industrial noise from electrical machinery coupled with the great distance (700 nm) between the St. Paul Island master station could cause low signal to noise ratio problems. In addition, three AM broadcast stations in Anchorage are separated by 100 KHz:

KENI - 550 KHz - 5 KW (daytime)
KYAK - 650 KHz - 50 KW (daytime)
KFQD - 750 KHz - 50 KW (daytime)

Although the receiver has high out-of-band rejection, it is possible for some energy from these frequencies to be present in the receiver front-end and cause synchronous interference at 100 KHz.

The rugged mountains in the test area create the likelihood of distortion of the Loran-C pulse. This type of distortion can create difficulties in identifying and tracking the third cycle zero crossing which is generally used by Loran-C receiver designers for phase tracking. Large ECD variation in mountainous areas were noted in other tests in the western U.S.[6]

The widespread occurrence of cycle tracking problems throughout the test area tends to enforce the pulse distortion theory. However,

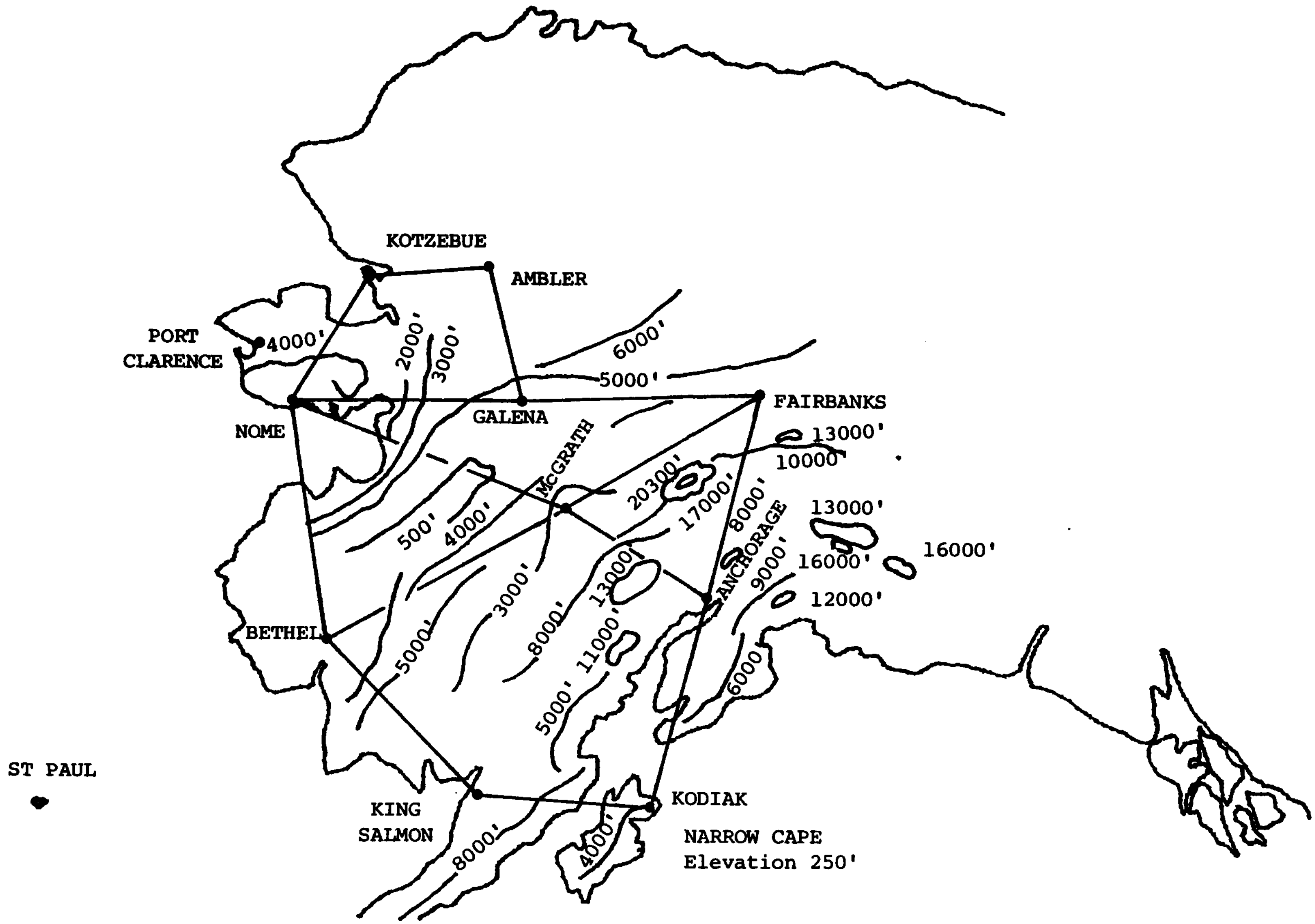

Figure 6.16 Mountainous Regions in the Flight Test Area

the amount and character of the recorded data are not sufficient to confirm or deny any of the listed problem sources nor to rule out other possible sources of problems.

Of major concern are the large number of cycle tracking problems observed in these tests. These errors produce large position errors as shown in Table 6.1 under the northing and easting error columns. The TDL-711 system is incapable of detecting these cycle tracking problems at the present time and therefore provides no warning to the pilot.

Of lesser concern for enroute IFR certification are the propagation modeling errors. These errors are generally quite repeatable and capable of being reduced by improved modeling or the use of published corrections. These errors will be of conern if IFR approach certification criteria are to be met in the future.

A statistical combination of the time difference and position errors for four cities in good coverage areas are shown in Table 6.2. These data show generally good position accuracy capability in spite of the occasional occurrences of cycle tracking problems.

Table 6.2 Statistical Combination of Time Difference and Position Errors

LOCATION	# PTS	μS TDA		μS TDB		NM ΔN		NM ΔE	
		$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ
KING SALMON	287	-3.62	.92	-3.37	.46	-.43	.15	-.37	.06
BETHEL	308	-1.72	1.07	-5.21	1.19	-.10	.09	-.50	.12
ANIAK	242	- .81	.61	-1.79	3.81	-.06	.06	-.19	.40
NOME	514	1.72	4.53	-1.34	4.80	.21	.64	-.22	.62

6.3.3 Coordinate Conversion Performance

The procedure for converting time difference measurements to latitude and longitude values was checked at several points in the test area. In all instances the procedure introduced less than .02 nm error. Therefore, the coordinate conversion procedure introduces negligible error into the system performance.

6.3.4 Guidance Computation Performance

The computation of distance to waypoint and crosstrack deviation was checked throughout the test area. The crosstrack error differed by less than .03 nm and the distance to waypoint differed by less than

0.1 nm, which was the resolution of the recorded data. Therefore, the guidance computation procedure introduces negligible error into the system performance.

6.4 PILOT PERFORMANCE

During the transition flights to and from Alaska and the test in Alaska, a linear CDI scale factor of ±1.28 nm full scale was used. Through use of the observers notes, the portions of the flight that Loran-C was being used for guidance were identified. These times were coupled with times when both Loran-C and DME position data were valid. CDI deflection data for these times are shown for flights 9-04, 9-06, 9-07 and 9-09 in Appendix B. In addition, statistical aggregation of the flight technical error (FTE) was performed for the four flights and for the total flight test period. These data are shown in Table 6.3. The data from flight 9-10 are essentially similar to those obtained on the first four days. However, because of the unavailability of DME positioning data during most of the flight, the data was not included in the statistical processing.

Table 6.3 Flight Technical Error

FLIGHT DATE	NUMBER OF POINTS	MEAN	STD DEVIATION
9-04-82	582	+.036	.103
9-06-82	578	+.033	.160
9-07-82	249	-.074	.193
9-09-82	872	-.005	.205
TOTAL	2281	+.007	.175

The flights often encountered high winds and moderate turbulence. In spite of these conditions, the data shows that FTE is considerably smaller than the 2.0 nm value contained in Advisory Circular 90-45A for enroute performance. The 95% level (2σ) for FTE as determined by the test data was 0.35 nm. This is approximately one-sixth of the value used in the advisory circular.

6.5 PHOTOGRAPHIC DATA

Table 6.4 summarizes the results of Alaska Loran-C data collected with the photographic data collection system on the Bethel Spur Route. The data is shown for six selected locations in the area west and north of Bethel. The summary of the error quantities in the table presents the error values for four specific parameters: Northing error (N-error), Easting error (E-error), crosstrack error (XTK-error and alongtrack error (ATK-error).

Table 6.4 Bethel Spur Route Error Quantities

LOCATION	COURSE	N-ERROR	E-ERROR	XTK-ERROR	ATK-ERROR
KIPNUK	347°	-.375	.438	.339	-.466
	167°	-.316	.417	-.333	.404
MEKORYUK	67°	-.092	.434	.257	.362
	247°	-.087	.482	-.271	-.408
NIGHTMUTE	219°	-.045	.415	-.350	-.228
	39°	-.036	.425	.352	.241
CAPE ROMANZOF	37°	-.131	.367	.371	.116
	37°	-.126	.361	.364	.117
RUSSIAN MISSION	11°	-.277	.532	.575	-.174
	191°	-.207	.552	-.581	.101
BETHEL	24°	-.352	.485	.587	-.124
	24°	-.325	.329	.432	-.163

Table 6.4 shows the northing error at Kipnuk to be -.375 nm while the easting error is .438 n. The largest easting error was encountered at Russian Mission, .552 n. Table 6.5 presents a statistical summary of the error quantities in Table 6.4. Mean and one-sigma values were calculated. Table 6.5 shows in the northing error case that the calculated mean is -.197 nm and the one-sigma value is .126 nm and a one-sigma value of .067 nm.

Table 6.5 Bethel Spur Route Error Statistics

	N-ERROR	E-ERROR	XTK-ERROR	ATK-ERROR
$\overline{X}$	-.197	.436	.145	-.019
σ	.126	.067	.408	.285
POINTS	12	12	12	12

As shown in Table 6.4 the largest crosstrack value was at Bethel, .587 nm. In the alongtrack direction the largest error was at Kipnuk, -.466 nm. The error statistics in Table 6.5 show that the calculated mean is .145 nm and the one-sigma value is .408 nm, for the crosstrack case. In the alongtrack direction the calculated mean was -.019 nm and a one-sigma of .285 nm.

The values indicated in Tables 6.4 and 6.5 support the fact that the TDL-711 system performs very accurately in the Bethel area. As shown in the tables, each location was flown twice, therefore

demonstrating the repeatable accuracy of the system in good coverage areas.

Comparison of the photo data with the DME positioning data for Bethel on the same day shows excellent agreement. The DME system produced northing and easting errors of -.369 and +.427 nm, respectively. These values agree very well with the northing errors of -.352 nm, and fall in between the easting errors of .485 and .329 nm.

6.6 OVERALL SYSTEM PERFORMANCE

Overall the performance of the navigator during the Alaska flights was quite variable. The performance in the Anchorage and Fairbanks areas, at the present time, is not acceptable for IFR navigation. Performance is areas west of the mountainous portions of the test area around King Salmon, Bethel, Aniak and Nome was sufficient to meet Advisory Circular 90-45A standards for RNAV enroute accuracy.

Total system errors for flights 9-04, 9-06, 9-07 and 9-09 are shown in Appendix C. These plots contain only points for which the DME positioning system with the Loran-C navigator were functioning, and during times when the pilots were using the Loran-C for guidance. Points where diversions for ATC vectors, weather avoidance and waypoint turnpoints were also deleted from the plots.

Statistical processing of this same data was performed to produce total system alongtrack (TSAT) errors and total system crosstrack (TSCT) errors. These data are shown in Table 6.6.

Table 6.6 Total System Errors

FLIGHT DATE	ERROR TYPE	# PTS	MEAN ($\bar{x}$)	STD DEV (σ)	MEAN +2σ	MEAN -2σ
9-04-82	TSAT	582	-.245	.241	.237	- .727
	TSCT	582	.359	.347	1.053	- .335
9-06-82	TSAT	578	-.428	.889	1.350	-2.206
	TSCT	578	.226	.428	1.082	- .630
9-07-82	TSAT	249	-.194	.129	.064	- .452
	TSCT	249	.268	.287	.842	- .306
9-09-82	TSAT	872	-.229	.441	.653	-1.111
	TSCT	872	.013	.457	.927	- .901
TOTAL	TSAT	2281	-.280	.546	.812	-1.372
	TSCT	2281	.183	.431	1.045	- .679

<u>/NOTE/</u> TSAT = Total System Along Track Error
TSCT = Total System Cross Track Error

The data shows that TSCT was within the 2.5 nm enroute criteria throughout the test program. TSAT does exceed the 1.5 nm criteria in some instances on flight 9-06. However, the aggregation of alongtrack error over the total test program stays within the +1.5 nm limit as shown in Table 6.6.

The area in which the receiver met or exceeded the accuracy requirements of Advisory Circular 90-45A in Alaska are shown in Figure 6.17. This area is defined on the east by the 156°W meridian, on the west by the 168°W meridian, on the south by the 58°N parallel and on the north by the 65°N parallel. The TDL-711 system repeatedly operated within the referenced accuracy criteria in this region. On some occasions the system worked accurately in areas east of the specified region; however, the performance was not sufficiently repeatable in these areas to confidently utilize the system for IFR navigation. Additional testing may permit expansion of the operational coverage area.

Loran-C navigation within the operational area in Figure 6.17 should be checked for accuracy upon system acquisition, and at regular intervals thereafter. These checks should be made with reference to other aircraft system navigation aids such as VOR, DME and ADF or by visual methods, if conditions permit.

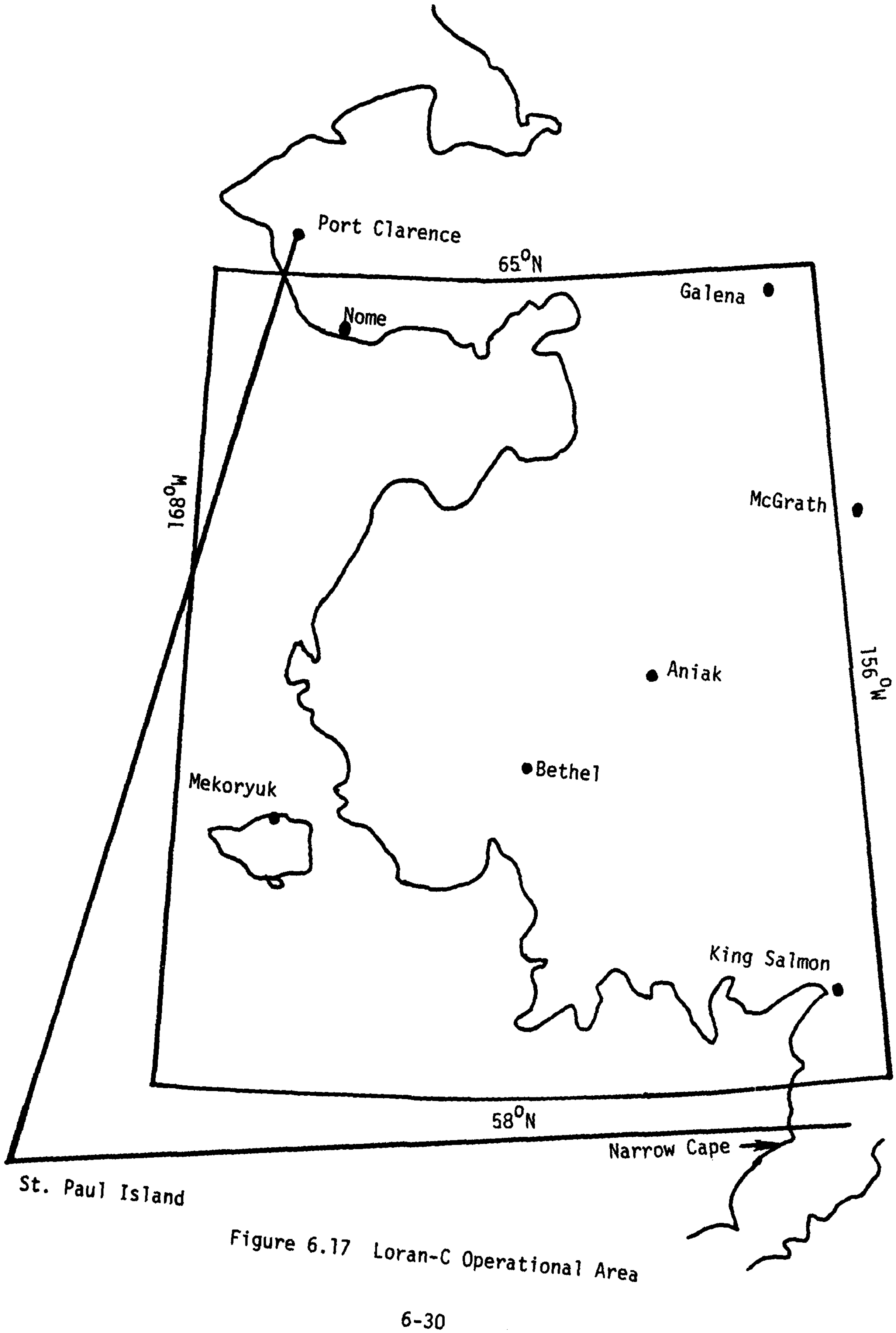

Figure 6.17 Loran-C Operational Area

7.0 CONCLUSIONS

The following conclusions were developed from the flight test of the Teledyne TDL-711 in Alaska:

- Total system alontrack and crosstrack errors were measured during the Alaska test at times when:
  - Loran-C was used for guidance
  - DME position data was available
  - The Loran-C system acquired and tracked the correct signals

  The accuracy met Advisory Circular 90-45A criteria at these times.
- Flight technical errors of 0.35 nm (2σ) were measured during the test.
- The TDL-711 system performed very poorly within at least a 60 nm radius of Anchorage. Position errors in excess of 15 nm were not uncommon. System accuracy in the Fairbanks area was also very poor.
- One of the most important problems encountered is that the system can lock-on to, and track, an erroneous signal and calculate erroneous guidance with no indication to the operator that it has done so. This error is translated into position and guidance error through the coordinate conversion process.
- A second probable source of time difference error observed during the test is propagation modeling error. This error was most apparent when operating near Nome and Kodiak. At these locations the magnitude of the modeling error approached 5 to 6 microseconds. This error in turn produced position error on the order of 0.9 nm at these locations.
- The TDL-711 performed very accurately in the areas around Nome, Bethel, Aniak and King Salmon. The system met or exceeded the enroute accuracy requirements of Advisory Circular 90-45A in these areas.
- The TDL-711 was easy to operate and imposed no undue burden on the flight crew.

REFERENCES

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APPENDIX A

DATA PROCESSING ALGORITHMS

This Appendix contains data processing equations that were used to 1) determine the aircraft position from DME measurements, and 2) compute system accuracy parameters. The equations for the minimum mean squared DME residual error and the DRMS position error estimate are developed in the appendix. Equations for great circle distance and bearing over a spherical earth are also included in the section. These equations were obtained from navigational texts.

A.1 MINIMIZATION OF THE MEAN SQUARED RESIDUAL ERROR

Figure A.1 presents the geometric configuration of the residual error problem. Assume that the current estimate of the aircraft's position is at P_1. Also assume that after correction the estimated position of the aircraft is at P_2. The position P2 is east of P_1 by an amount ΔE and north of P_1 by an amount of ΔN. The computed distance from the current position is D_c and the measured distance from the DME is D_m. The DME error is then expressed as

$$\Delta D_i = D_m - D_c = \Delta E \sin \beta_i + \Delta N \cos \beta_i + \text{Residual}_i$$

where β_i is the azimuth from the i th DME station to the estimated aircraft position P_1 as measured at P_1, and Residual_i is any remaining error after the shift from P_1 to P_2 is made.

Solving for Residual_i

$$\text{Residual}_i = R_i = \Delta D_i - \Delta E \sin \beta_i - \Delta N \cos \beta_i$$

and squaring

$$\begin{aligned} R_i{}^2 = {} & \Delta D_i{}^2 + \Delta E^2 \sin^2 \beta_i + \Delta N^2 \cos^2 \beta_i \\ & - 2\,\Delta D_i\,\Delta E \sin \beta_i - 2\Delta D_i\,\Delta N \cos \beta_i \\ & + 2\,\Delta E\,\Delta N \sin \beta_i \cos \beta_i \end{aligned}$$

The mean value of the squared residual errors is

$$\begin{aligned} \Sigma R_i{}^2 = {} & \Sigma\Delta D_i{}^2 + \Delta E^2\, \Sigma \sin \beta_i{}^2 + \Delta N^2\, \Sigma \cos^2 \beta_i \\ & - 2\Delta E\, \Sigma\Delta D_i \sin \beta_i - 2\Delta N \Sigma\Delta D_i \cos \beta_i \\ & + 2\,\Delta E\,\Delta N\, \Sigma \sin \beta_i \cos \beta_i \end{aligned}$$

where Σ represents the summation over the number of available DME stations.

The minimumization is performed by extracting the partial derivatives of the mean squared residual error with respect to the unknowns ΔE and ΔN and setting these derivatives to zero.

$$\begin{aligned} \frac{\partial \Sigma R_i{}^2}{\partial E} = 0 = {} & 2\,\Delta E\, \Sigma \sin \beta_i{}^2 - 2\, \Sigma\Delta D_i \sin \beta_i \\ & + 2\,\Delta N\, \Delta \sin \beta_i \cos \beta_i \end{aligned}$$

$$\begin{aligned} \frac{\partial \Sigma R_i}{\partial N} = 0 = {} & 2\,\Delta N\, \Sigma \cos^2 \beta_i - 2\, \Sigma\Delta D_i \cos \beta_i \\ & + 2\,\Delta E\, \Sigma \sin \beta_i \cos \beta_i \end{aligned}$$

Collecting terms

$$\begin{bmatrix} \Sigma\Delta D_i \sin \beta_i \\ \Sigma\Delta D_i \cos \beta_i \end{bmatrix} = \left[\begin{array}{c:c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \cos \beta_i & \Sigma \cos^2 \beta_i \end{array}\right] \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix} \qquad \text{(Equation A.1)}$$

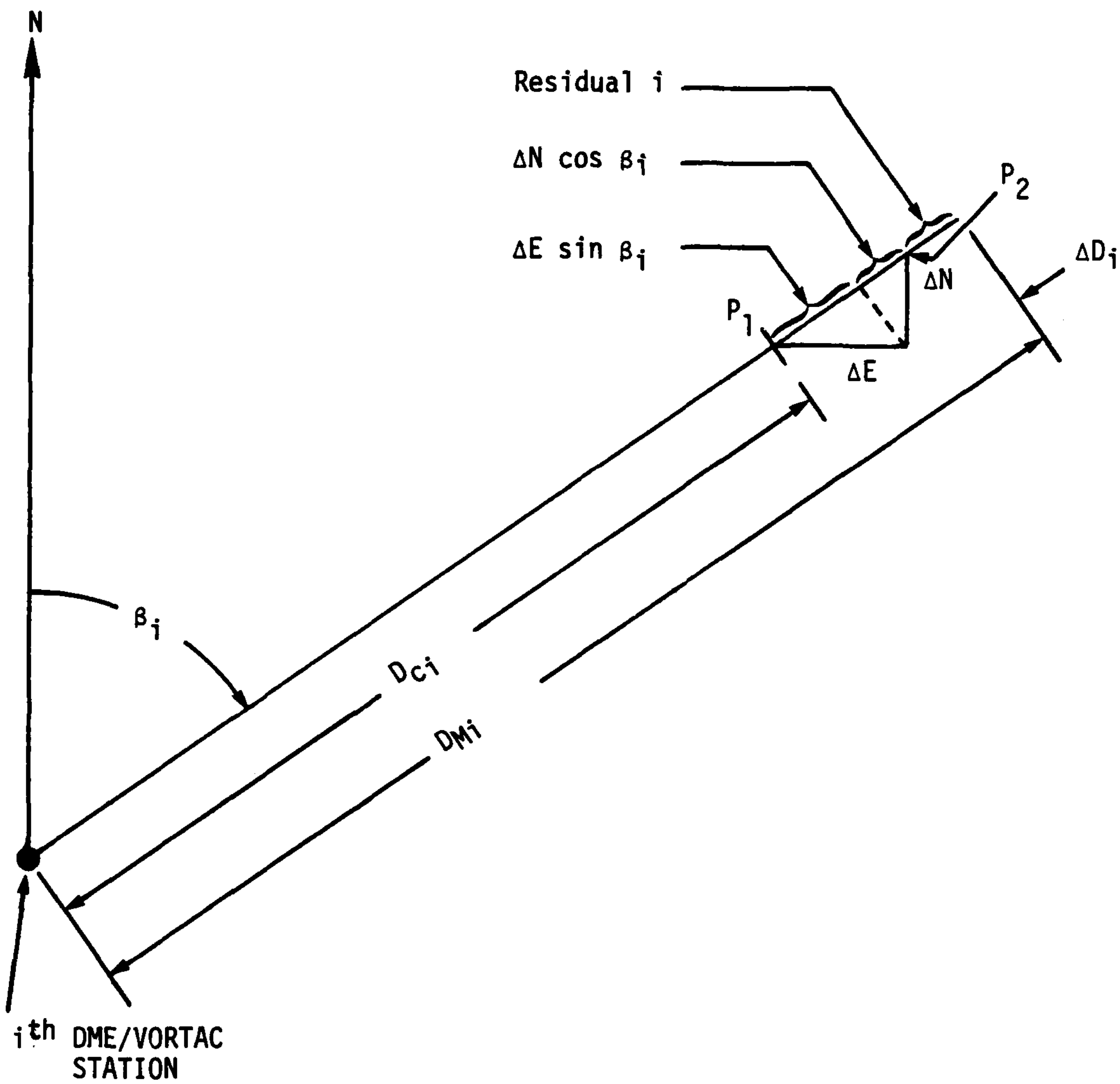


Figure A.1 Residual Error Geometry

Solving for ΔE and ΔN

$$\Delta E = \frac{(\Sigma \Delta D_i \sin \beta_i)(\Sigma \cos^2 \beta_i) - (\Delta \Sigma D_i \cos \beta_i)(\Sigma \sin \beta_i \cos \beta_i)}{(\Sigma \cos^2 \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

$$\Delta N = \frac{(\Sigma D_i \cos \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \Delta D_i \sin \beta_i)(\Sigma \sin \beta_i \cos \beta_i)}{(\Sigma \cos^2 \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

A.2 EVALUATION OF THE ROOT MEAN SQUARE POSITION ERROR (D_{RMS})

Equation A.1 can be utilized to develop the root mean square position error value which is the familiar D_{RMS} statistic. Expressed in matrix form Equation A.1 can be written

$$[\Delta D] = [A]\,[\Delta P]$$

where $[\Delta D] = \begin{bmatrix} \Sigma \Delta D_i \sin \beta_i \\ \Sigma \Delta D_i \cos \beta_i \end{bmatrix}$ a 2x1 matrix

$[A] = \left[\begin{array}{c|c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \Sigma \cos \beta_i & \Sigma \cos^2 \beta_i \end{array}\right]$ a 2x2 matrix

$[\Delta P] = \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix}$ a 2x1 matrix

The solution for $[\Delta P]$ can be written

$$[\Delta P] = [A^{-1}]\,[\Sigma D]$$

where $[A^{-1}]$ is the inverse of A

The covarience matrix can be evaluated by multiplying $[\Delta P]$ by its transpose, $[\Delta P]^T$, and averaging the result.

$$[\Delta P]^T = [A^{-1}]\,[\Delta D]^{\;T} = [\Delta D]^T [A^{-1}]^T = [\Delta D]^T [A^{-1}]$$

Since A is symmetrical $[A]^T = [A]$ and $[A^{-1}]^T = [A^{-1}]$.

$$[\text{cov } \Delta P] = E\left\{[\Delta P]\,[\Delta P]^T\right\} = E\left\{[A^{-1}]\,[\Delta D]\,[\Delta D]\,[A^{-1}]\right\}$$

where $E\{\;\}$ represents averaging.

Examining the right most term, the quantities in the A matrix are deterministic and can be brought outside the averaging process. This term then becomes

$$[\text{cov } \Delta P] = [A^{-1}]\left\{[\Delta D]\,[\Delta D]^T\right\}[A^{-1}]$$

Expanding the averaging term

$$E\left\{[\Delta D]\,[\Delta D]^T\right\} = \begin{bmatrix} E\left\{\Sigma \Delta D_i \sin \beta_i \,\Sigma \Delta D_j \sin \beta_j\right\} & E\left\{\Sigma \Delta D_i \sin \beta_i \,\Sigma \Delta D_j \cos \beta_j\right\} \\ E\left\{\Sigma \Delta D_i \cos \beta_i \,\Sigma \Delta D_j \sin \beta_j\right\} & E\left\{\Sigma \Delta D_i \cos \beta_i \,\Sigma \Delta D_j \cos \beta_j\right\} \end{bmatrix}$$

(Equation A.2)

The averaging process depends upon the statistical character of the random variables ΔD_i and ΔD_j which are the errors in the DME measurements. These errors are of two types, those associated with the station and these associated with the receiver. For this analysis it is assumed that station errors are much geater than receiver errors. Furthermore, it is assumed that the ensemble of station errors have zero mean error and a standard deviation of σ_D and the station errors are independant of each other, which implies that the correlation between stations, ρ_{ij} is zero for $i \neq j$. Under these assumptions, equation A.2 becomes

$$E\left\{[\Delta D]\,[\Delta D]^T\right\} = \sigma_D^2 \begin{bmatrix} \Sigma\sin^2\beta_i & \Sigma\sin\beta_i\cos\beta_i \\ \Sigma\sin\beta_i\,\Sigma\cos\beta_i & \Sigma\cos^2\beta_i \end{bmatrix}$$

$$= \sigma_D^2[A]$$

The matrix on the right is the matrix [A]. Therefore, the convarience matrix becomes

$$[\mathrm{cov}\ \Delta P] = \sigma_D^2[A^{-1}]\,[A]\,[A^{-1}] = \sigma_D^2[A^{-1}]$$

or expanding

$$\begin{bmatrix} \sigma_E^2 & \rho_{EN}\sigma_E\,\sigma_N \\ \rho_{EN}\,\sigma_E\,\sigma_N & \sigma_N^2 \end{bmatrix} = \sigma_D^2\,\frac{\begin{bmatrix} \Sigma\cos^2\beta_i & -\Sigma\sin\beta_i\Sigma\cos\beta_i \\ -\Delta\sin\beta_i\cos\beta_i & \Sigma\sin^2\beta_i \end{bmatrix}}{\Sigma\sin^2\beta_i\ \ \Sigma\cos^2\beta_i-(\Sigma\sin\beta_i\cos\beta_i)^2}$$

The trace of the matrix on the left is recognized as the square of the D_{RMS} statistic. Therefore,

$$D^2_{RMS} = \frac{\sigma_D^2(\Sigma\cos^2\beta_i + \Sigma\sin^2\beta_i)}{\Sigma\sin^2\beta_i\ \Sigma\cos^2\beta i-(\Sigma\sin\beta_i\cos\beta_i)^2}$$

which, upon inspection, reduces to

$$D^2_{RMS} = \frac{M\,\sigma_D^2}{\sum\limits_{i=1}^{M}\ \sum\limits_{j=i+1}^{M}\sin^2(\beta_i - \beta_j)}$$

where M is the number of DME stations.

A.3 GREAT CIRCLE DISTANCE AND COURSE EQUATIONS

The following equations were used to compute great circle distance (D) and course (ψ) from an origin at P_1 and a destination at P_2 over a spherically shaped earth:

$$D = 60 * \frac{180}{\pi} * \theta$$

$$\theta = 2\sin^{-1}\sqrt{\sin^2\left(\frac{\beta_1 - \beta_2}{2}\right) + \cos\beta_1 \cos\beta_2 \sin^2\frac{\Delta\lambda}{2}}$$

where θ is the central angle at the center of the earth β_1, β_2 are the latitude coordinates of P_1 and P_2 and $\Delta\lambda$ is the difference in longitude $(\lambda_2 - \lambda_1)$

$$\psi = \tan^{-1}\left(\frac{\sin A}{\cos A}\right)$$

where $\sin A = \dfrac{\cos\beta_2 \sin\Delta\lambda}{\sin\theta}$

$$\cos A = \frac{\sin\beta_2 - \sin\beta_1 \cos\theta}{\cos\beta_1 \sin\theta}$$

where ψ is the course at P_1.

The sign convention for ψ is shown in Figure A.2

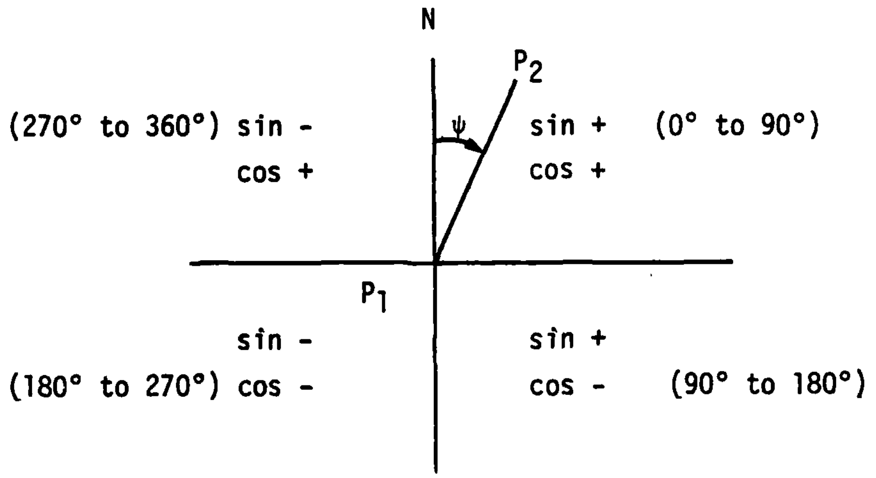


Figure A.2 Sign Convention for Course Computation

APPENDIX B

FLIGHT TECHNICAL ERROR PLOTS

Flight technical error data recorded during times when Loran-C was utilized for navigation and the DME positioning system was operational are shown in Figures B.1 through B.4. Each plot contains data for one daily flight.

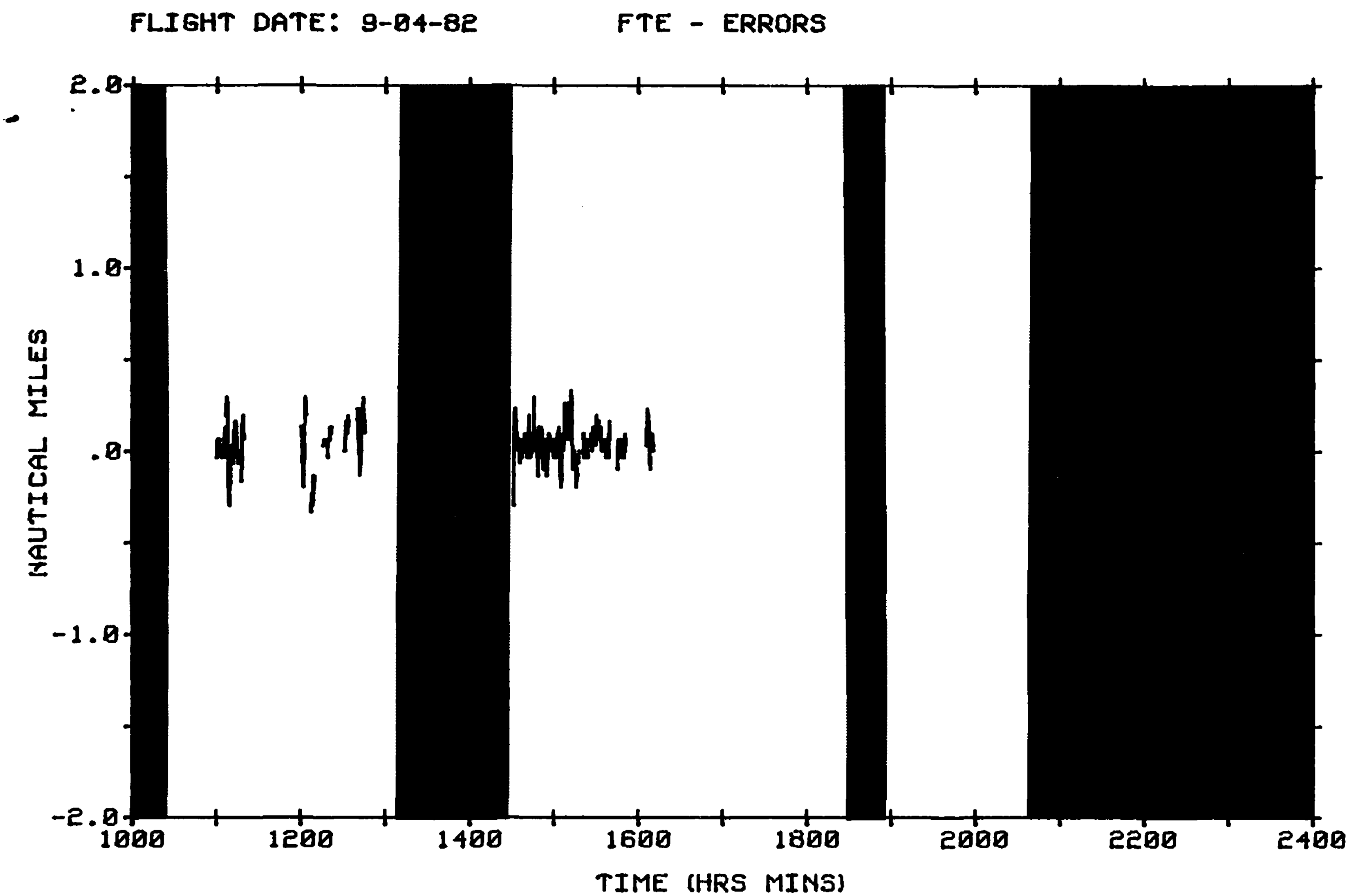


Figure B.1 FTE Errors, Flight 9-04

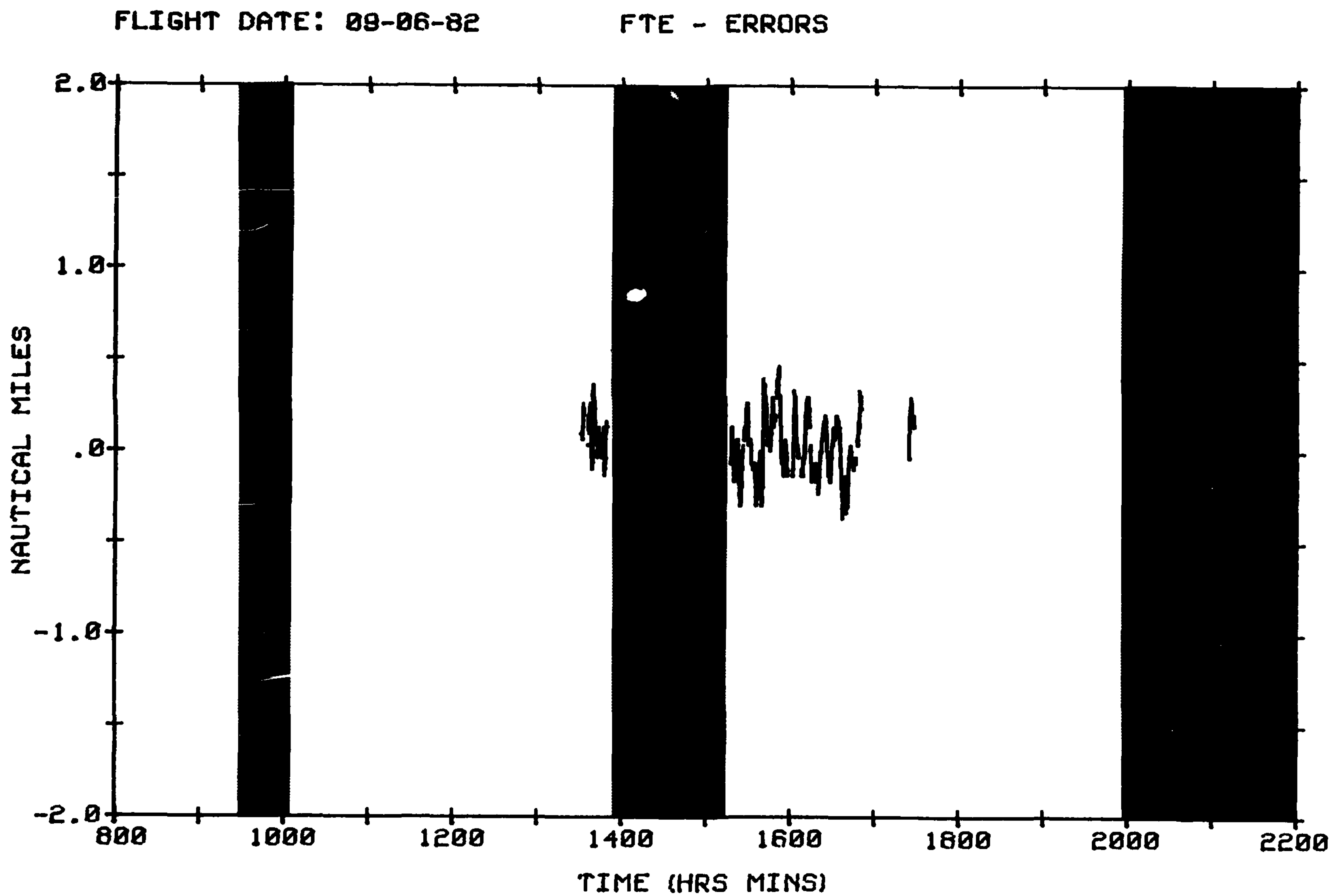


Figure B.2 FTE Errors, Flight 9-06

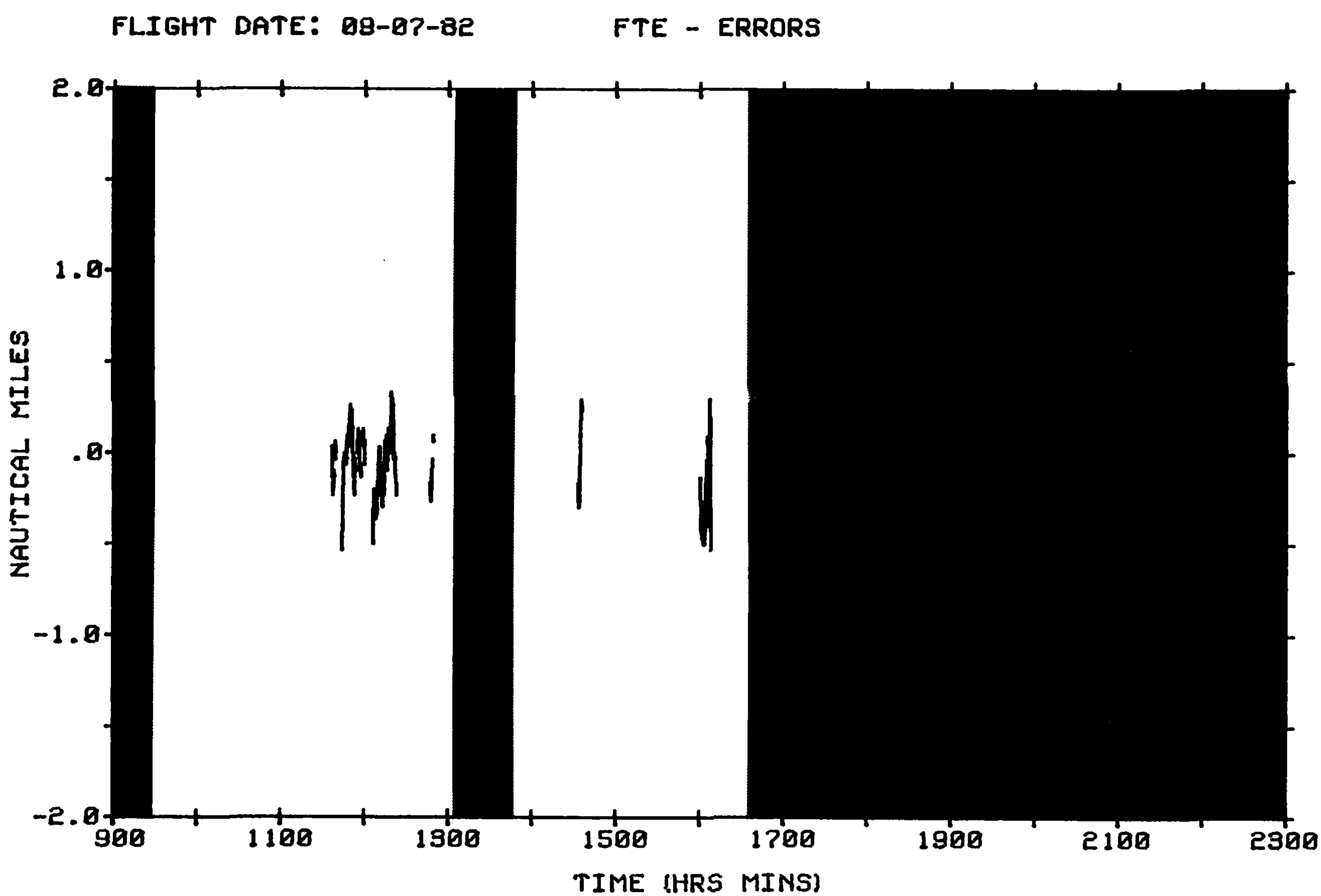


Figure B.3 FTE Errors, Flight 9-07

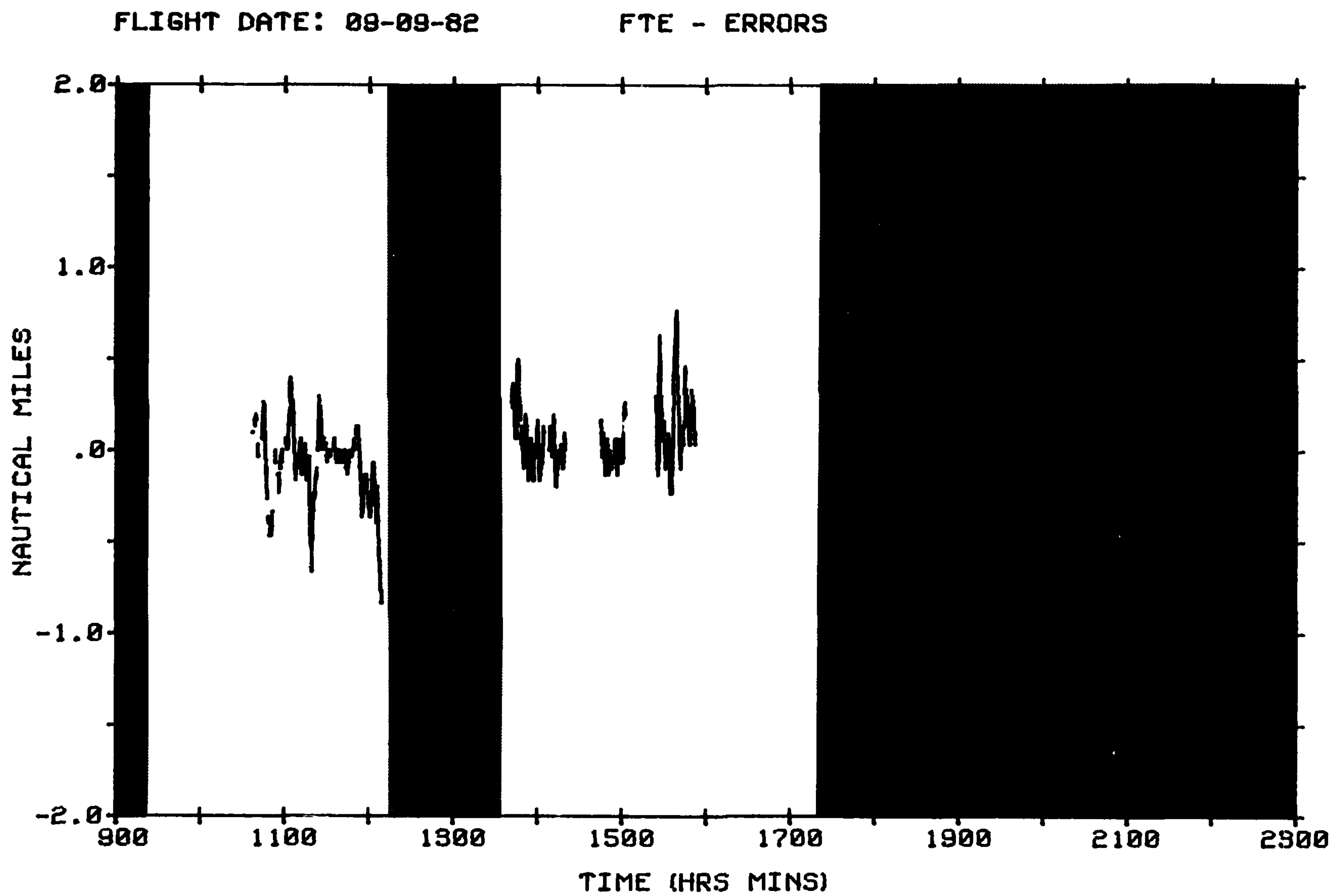
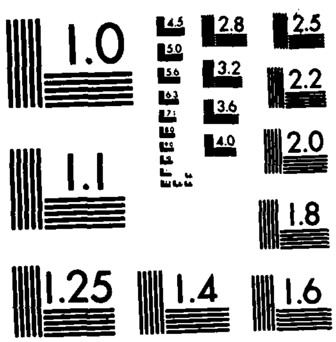


Figure B.4 FTE Errors, Flight 9-09

AD-A128 633 ALASKA LORAN-C FLIGHT TEST EVALUATION(U) SYSTEMS CONTROL TECHNOLOGY INC WEST PALM BEACH FL L D KING ET AL. MAR 83 DOT/FAA/PM-83/4 2/2

UNCLASSIFIED DOT-FA01-80-C-10080 F/G 14/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX C

TOTAL SYSTEM ERROR PLOTS

Total system error data recorded during times when Loran-C was utilized for navigation and the DME positioning system was operational are shown in Figure C.1 through C.8. Figures C.1 through C.4 present total system alongtrack errors (TSAT). Figures C.5 through C.8 present total system crosstrack errors (TSCT). Each plot contains data for one daily flight.

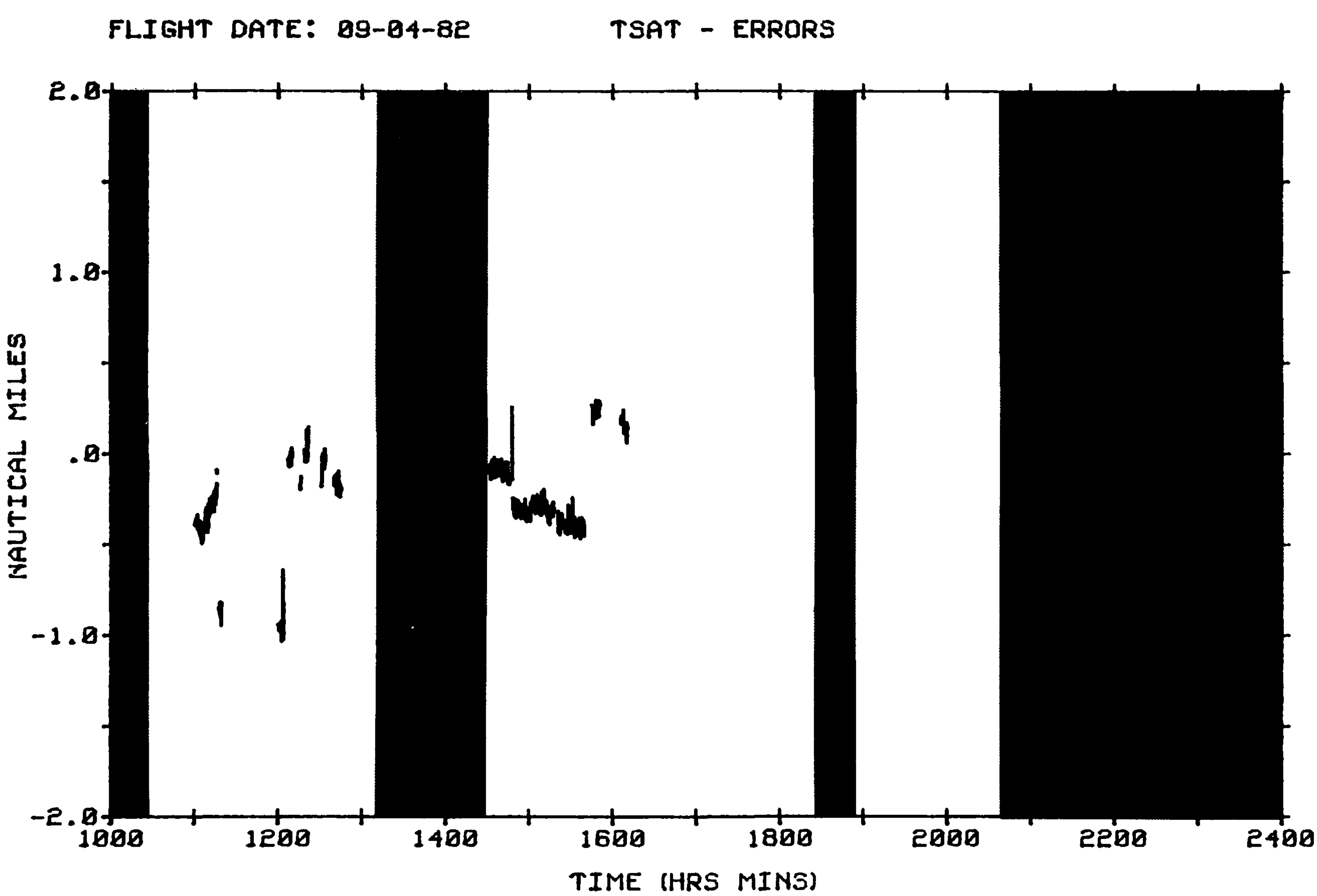


Figure C.1 TSAT Errors, Flight 9-04

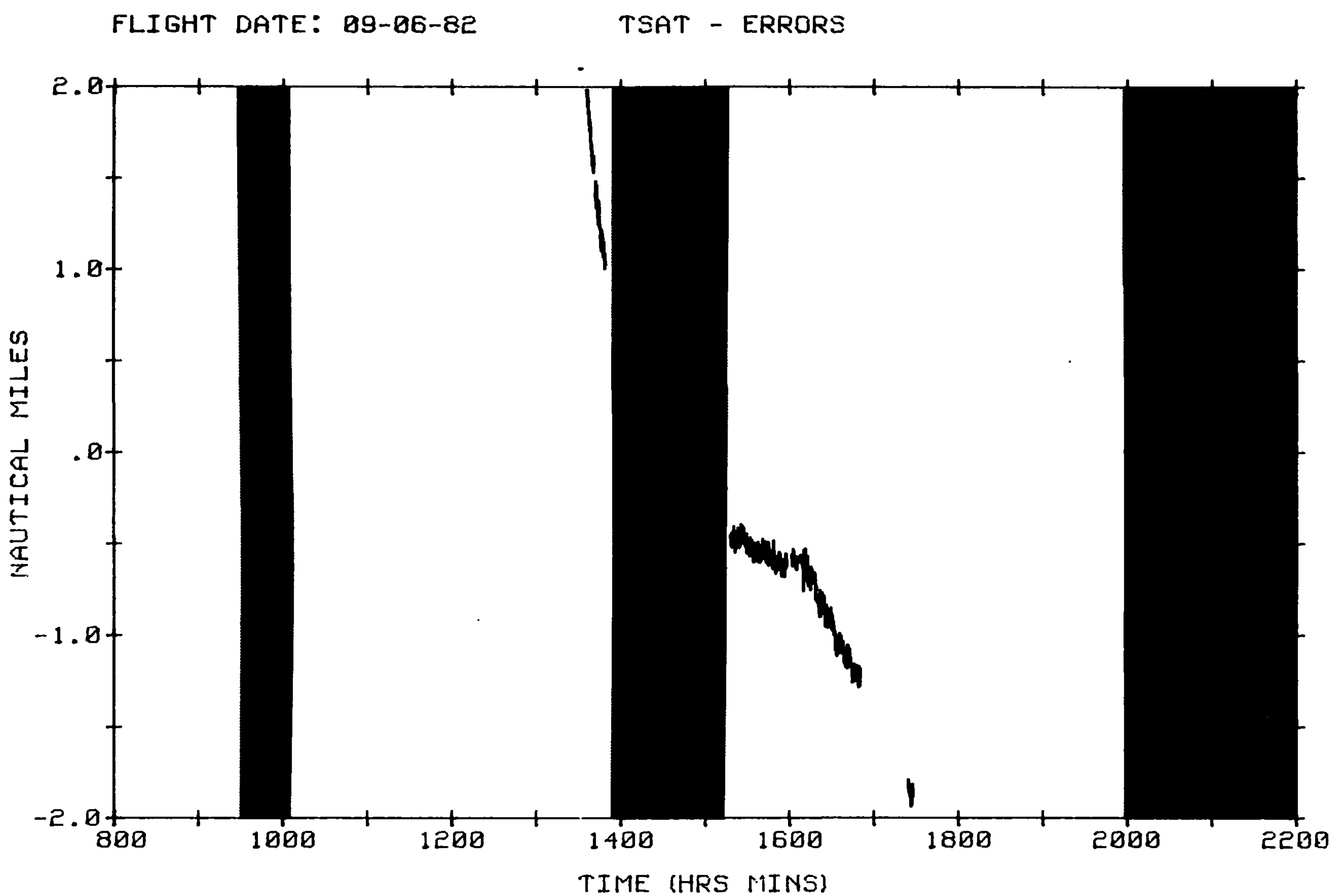


Figure C.2 TSAT Errors, Flight 9-06

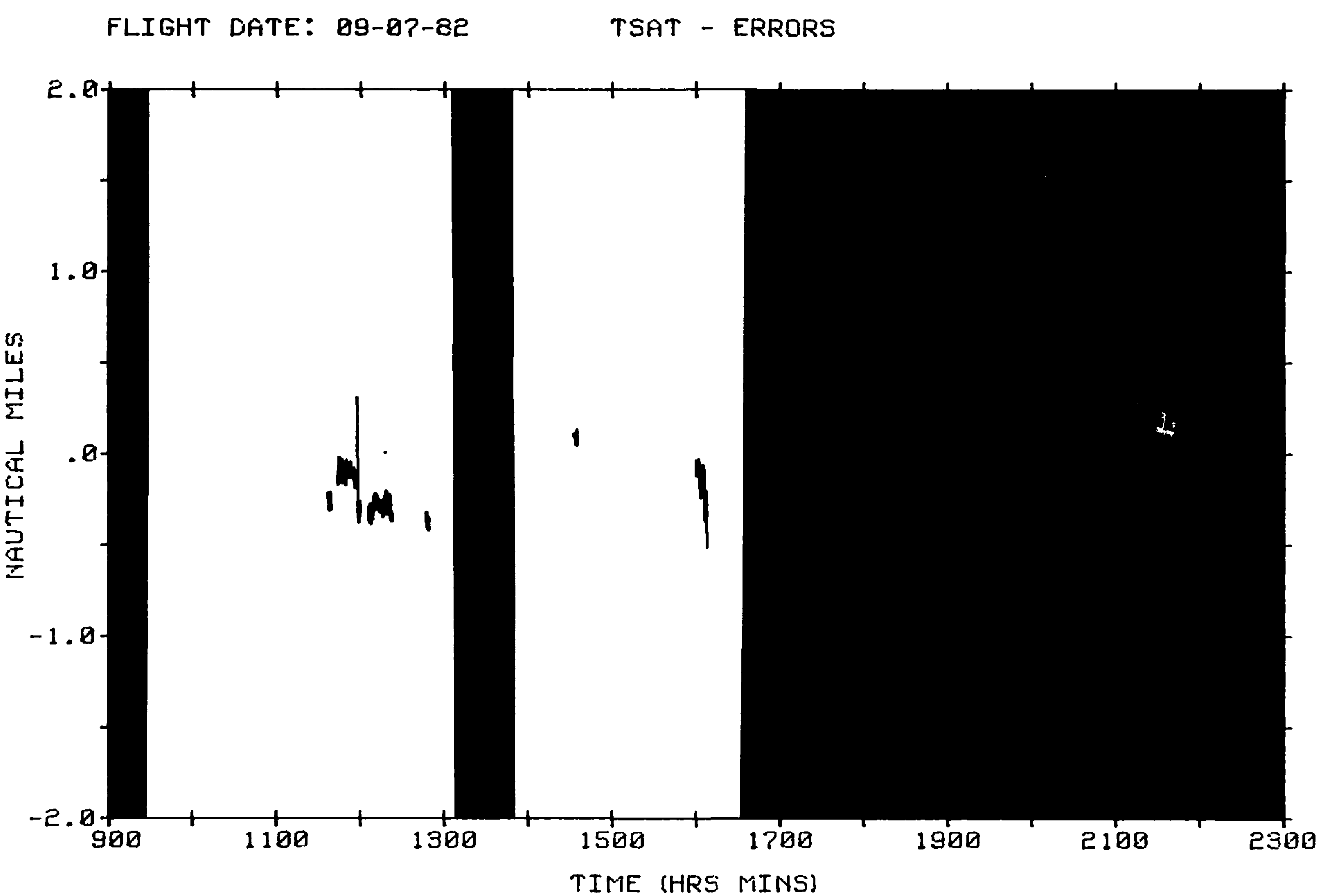


Figure C.3 TSA rors, Flight 9-07

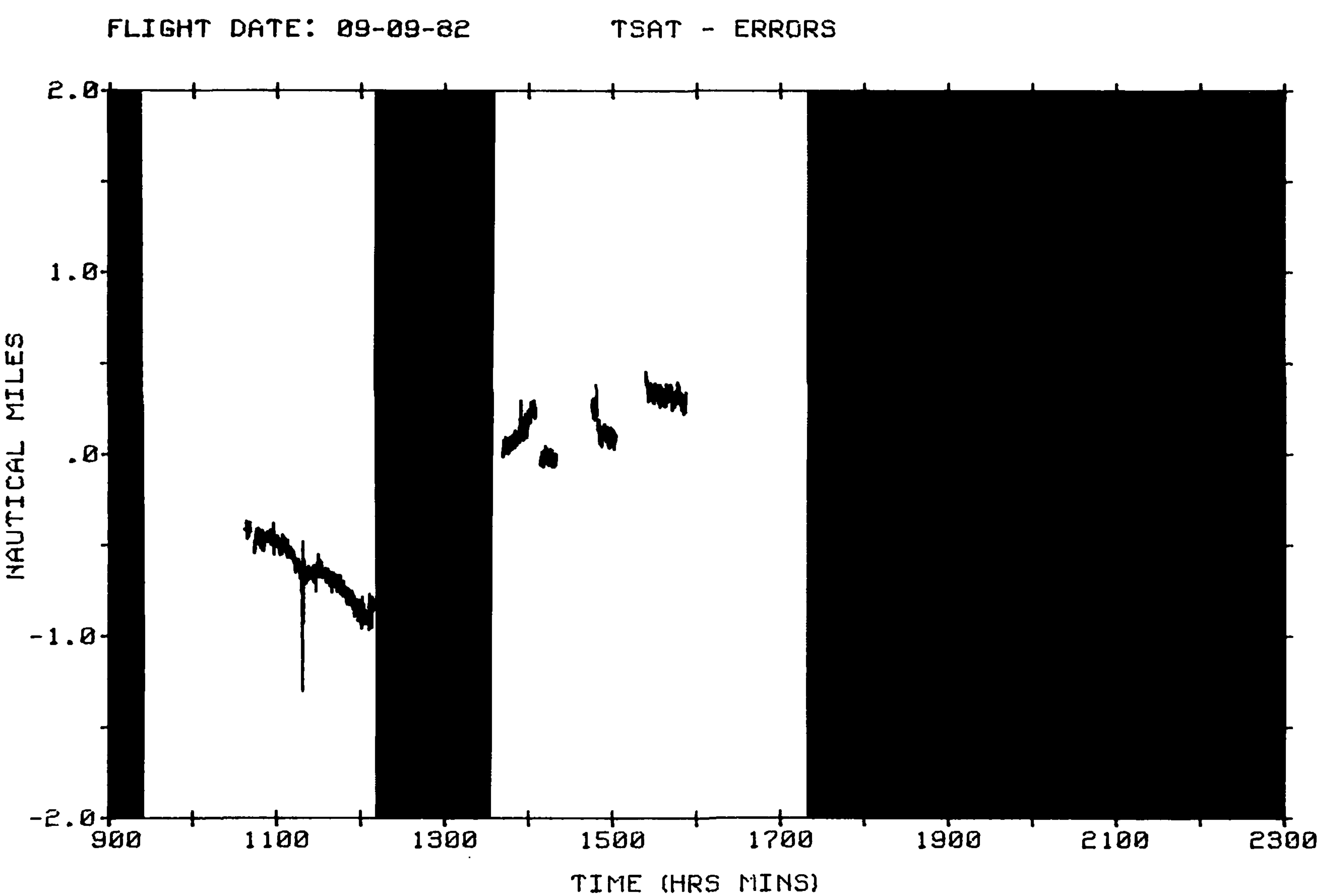


Figure C.4 TSAT Errors, Flight 9-09

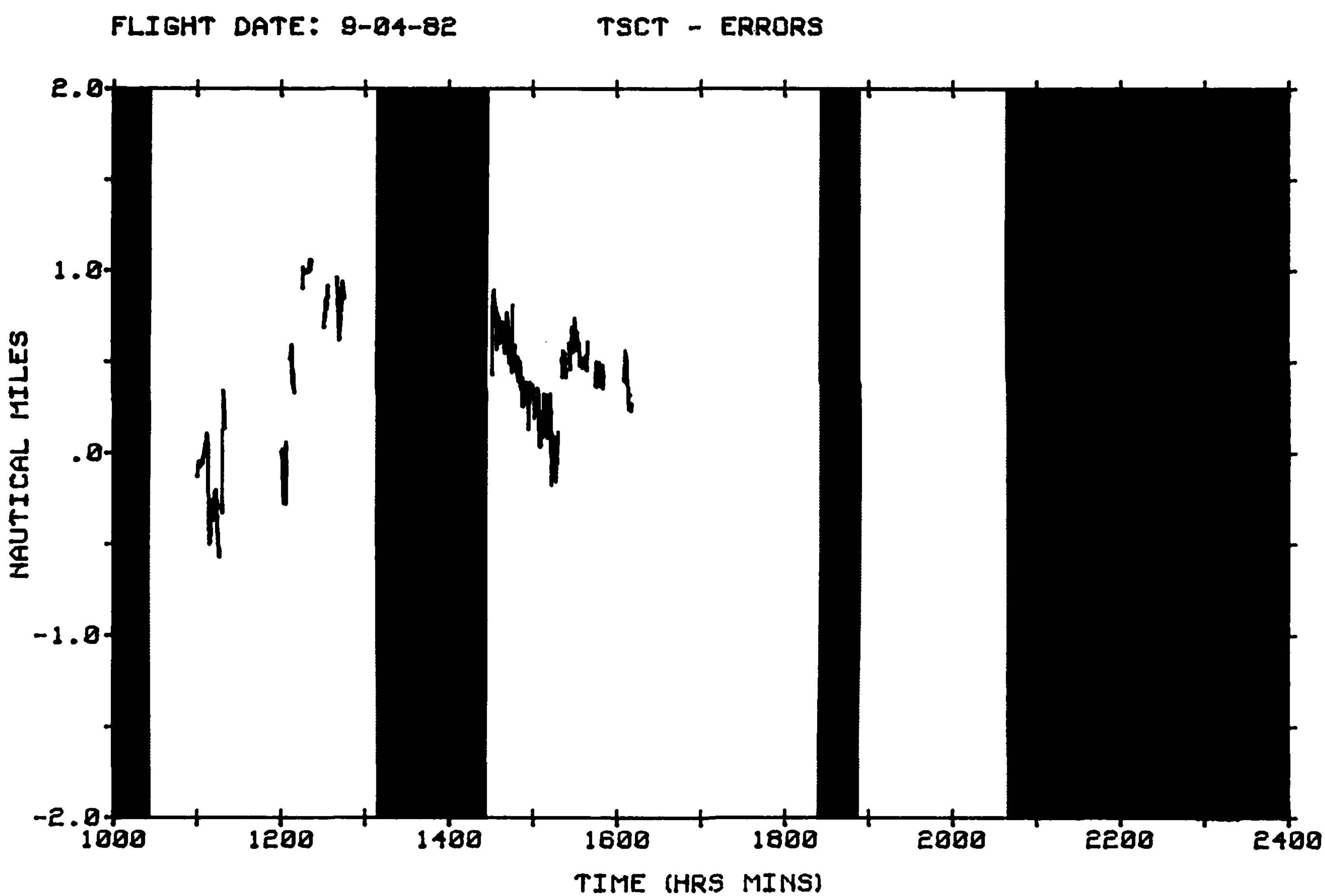


Figure C.5 TSCT Errors, Flight 9-04

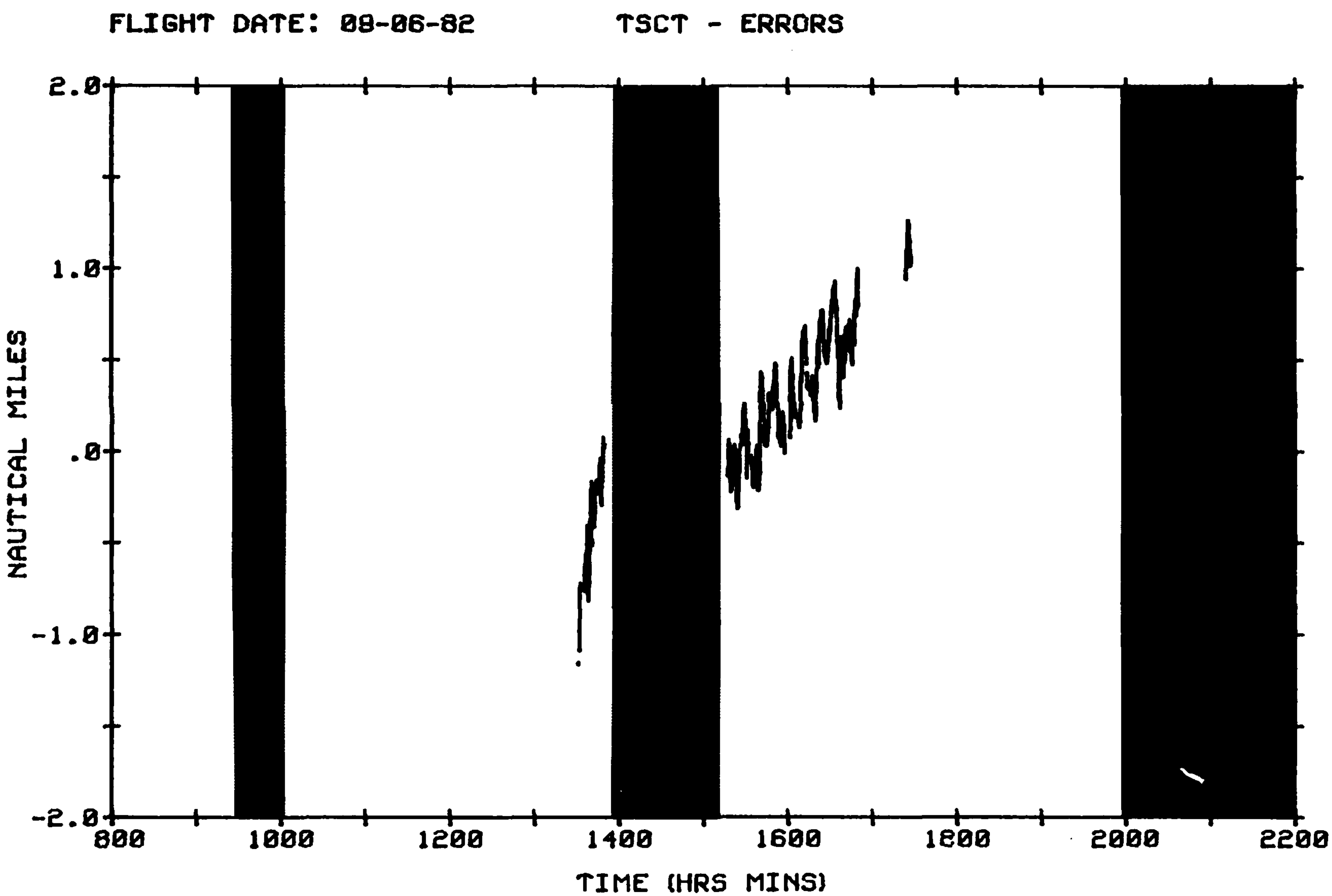


Figure C.6 TSCT Errors, Flight 9-06

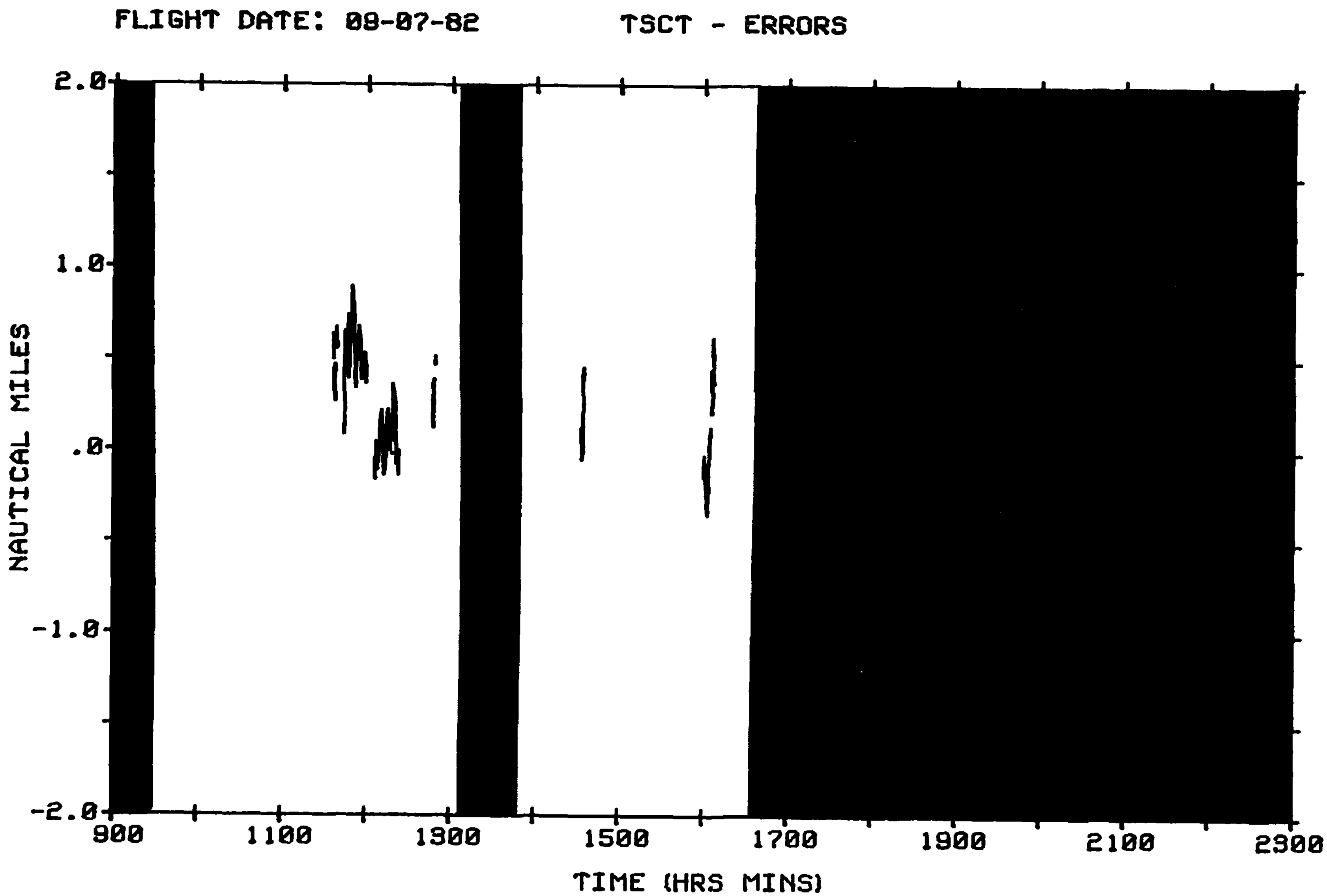


Figure C.7 TSCT Errors, Flight 9-07

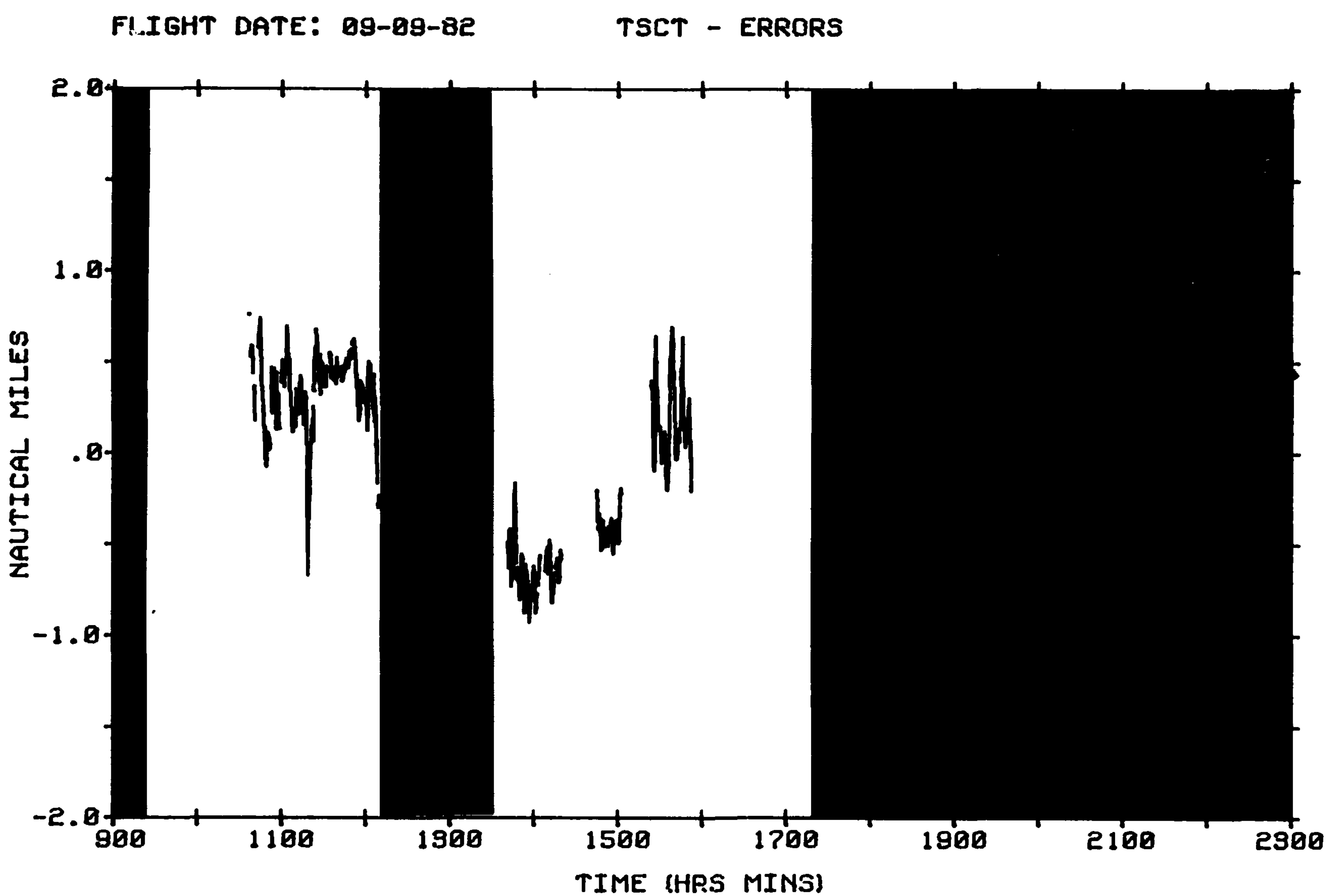


Figure C.8 TSCT Errors, Flight 9-09

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